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ON AN AURORAL EXPEDITION TO BOSSEKOP IN THE SPRING OF 1913

By CARL STÖRMER

The following is a short account of a new auroral expedition which I made to Bossekop in the spring of 1913 for the purpose of completing the results of my expedition[1] to the same place in 1910.

My assistant was the meteorologist, Bernt Johannes Birkeland, who also went with me in 1910, and is going with Roald Amundsen's expedition over the North Polar basin.

The purpose of the expedition was mainly to obtain more accurate, more numerous auroral photographs for the determination of the form of aurora, and its height and situation in space, and further to experiment with objective-prism photographing and the taking of cinematograph films.

Our preparations and equipment were on the whole the same as in 1910; but the following improvements, based upon experience gained on that expedition, were carried out:

The cameras were furnished with an arrangement whereby a photograph of an illuminated watch-face was taken on the plate exactly simultaneously with the aurora. The time could then be read from the photograph, and also the exposure by the sector

[1] See "Bericht über eine Expedition nach Bossekop zwecks photographischer Aufnahmen und Höhenmessungen von Nordlichtern," mit 57 Figuren im Text und 88 Tafeln, *Videnskabsselskabets Skrifter, Math.-Naturv. Klasse 1911*, No. 17, Christiania.

described by the second-hand. This improvement I had already employed in photographing aurora in Christiania in the winter of 1910–1911.

In order to avoid the waste of time in changing plates in a dark room, each station, in addition to 40 cassettes, was furnished with changing-boxes in which the plates could be changed in the open air. Thanks to this improvement, it was possible on some evenings to take more than 80 simultaneous photographs at the two stations.

In order to have the arms at liberty, the following improvement in the telephone arrangement was made: The microphone and receiver were fixed to the chest and head, and connected with the field telephone apparatus by a cord 4 meters in length. In this way it became possible to utilize more fully the brief moments during which the aurora displayed its greatest intensity.

For the purpose of obtaining reliable parallaxes, a base of $27\frac{1}{2}$ kilometers was chosen, as against $4\frac{1}{2}$ kilometers in 1910. The station at which Birkeland took up his quarters was Store Korsnes, the other was Bossekop. As assistant at Bossekop I had engaged Sergeant Ottem. The direction from Bossekop to Store Korsnes was almost due north.

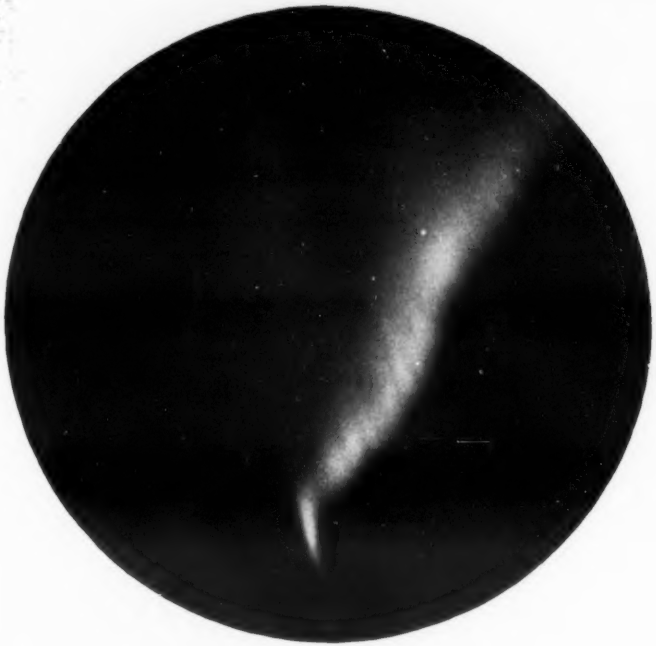
Through the courtesy of the Telegraph Department, the state telephone line from Bossekop to Korsnes was placed at our disposal every night from 7:30 P M.

As a result of these arrangements, we succeeded in one month in taking the following pairs (see table on p. 313) of simultaneous auroral photographs at Bossekop and Korsnes.

On the 6 best evenings, March 11, 14, 15, 29, and 30, and April 1, the weather was clear and the aurora vivid and continuous, so that we were able to make use of every chance.

The parallaxes, thanks to the large base, were very distinct, as a rule between 5 and 15 degrees, and the large number of photographs—447 pairs as against 44 in 1910—gives very much more certain and complete results than on that occasion. If we reckon about 10 measurements to each photograph, these will give more than 4,000 reliable determinations of height. All important forms of aurora were photographed, and there are long series of developments.

PLATE VI



Photographed from Bossekop

Photographed from Store Korsnes

AURORAL DRAPERY WITH *Gemini*, MARCH 11, 1913, $12^h 33^m$. EXPOSURE 3 SEC.

PLATE VII

Photographed from Store Korsnes

Photographed from Bossekop

AURORA IN THE FORM OF A LUMINOUS TRANQUIL SURFACE, MARCH 11, 1913, $12^{h}53^{m}$. IN THE BACKGROUND ARE *Arcturus* AND *Gemma*

PLATE VIII

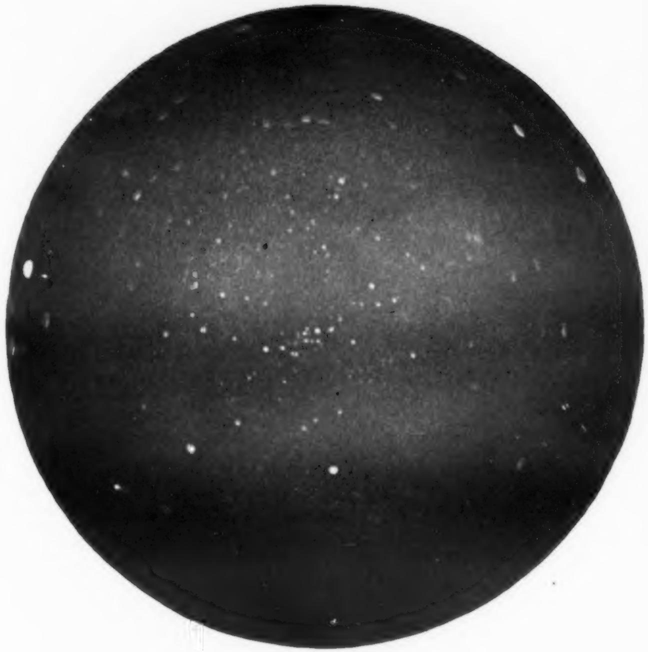
Photographed from Store Korsnes

Photographed from Bossekop

AURORA WITH *Vega*, MARCH 30, 1913, $10^{h}20^{m}$

PLATE IX

Photographed from Store Korsnes



Photographed from Bossekop

EXCEEDINGLY FAINT, HOMOGENEOUS AURORAL ARCS, WITH *Perseus*, APRIL 1, 1913, 12^h5^m

Some of the photographs are here reproduced (Plates VI–IX), enlarged about $2\frac{1}{4}$ times, one degree answering to 2 mm in the photograph. The time is Central European time and reckoned from 0^h to 24^h, 0^h answering to 12 noon.

Day	Number of Pairs Taken	Successful
February 28	14	0
March 3	38	19
" 4	23	9
" 6	7	1
" 11	86	58
" 14	81	54
" 15	81	72
" 16	8	2
" 17	14	7
" 18	5	5
" 21	23	20
" 22	20	12
" 23	1	1
" 24	6	6
" 28	5	3
" 29	83	64
" 30	71	62
April 1	70	52
Total	636	447

With an objective-prism we succeeded in taking some photographs simultaneously with the auroral photographs, on which are seen stellar spectra and some views of the aurora lying side by side, answering to various spectral lines. The prism[1] had an angle of 60° and was placed in front of the kinostigmatic objective, on the principle already mentioned in my "Bericht." A systematic employment of this method will be of great importance to the study of the highest strata of the atmosphere.

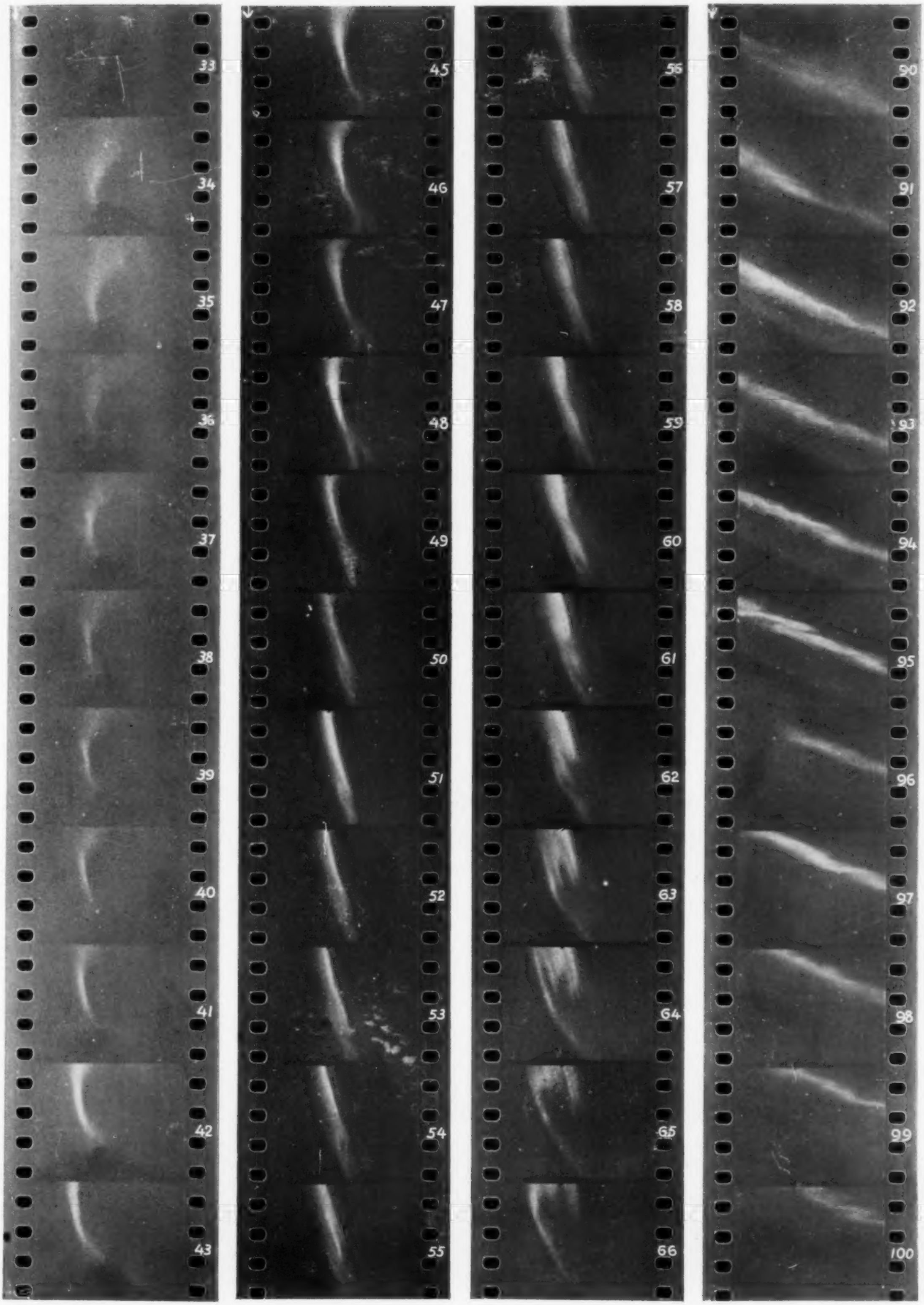
Most of the cinematograph attempts were failures, as the film (*Lumière*) was not as a rule affected by an exposure of less than 2 seconds. It was only with very intense aurora that we succeeded in getting good photographs with an exposure of about 1 second and with about 2 seconds' interval between the photographs. Two

[1] With regard to the kind of glass that would be best for the purpose, I received valuable information from Dr. Slipher when visiting the Flagstaff Observatory in the summer of 1912.

or three such series were taken, thus proving the utility of the cinematograph both for taking photographs and for registering rapid changes. Parts of a film of about 100 pictures are here given (Plate X), taken on the night between April 8 and 9, of an aurora in the west. Each picture was exposed from 3 to 5 seconds. The figures give the numbers in chronological order.

The working-up of the matter collected during the expedition will be the subject of a subsequent detailed account.

PLATE X



CINEMATOGRAPH PICTURES OF AURORA ON APRIL 8, 1913, BETWEEN 12^h AND 12^h15^m, BOSSEKOP

A STUDY OF THE RELATION OF ARC AND SPARK LINES BY MEANS OF THE TUBE-ARC[1]

By ARTHUR S. KING

In a recent paper,[2] the writer described the peculiarities in the spectra given by a special form of vacuum arc. The graphite tube employed in a tube resistance furnace was forced to high incandescence and made to burn through. An arc formed between the two sections of the tube in which currents as high as 800 amperes sometimes passed at a potential of about 30 volts. When the interior of the tube was observed axially, with titanium present, the spectrum given by this arc showed a predominance of those lines which are stronger in the spark than in the arc. By projecting an image of the interior of the tube on the slit of a plane-grating spectrograph, the strength of the spectrum lines was found to vary in different parts of the cross-section, the titanium enhanced lines being relatively strong in the center of the tube, while the lines characteristic of the arc showed most strongly near the wall. A strong line of carbon, λ 4267, usually appearing only in the spark, was very intense in the center of the tube and weak near the wall.

This source, which may appropriately be named the "tube-arc," has been used in further experiments which have confirmed and extended the previous results. In addition to the spectra of several metals and of carbon, the spectrum of hydrogen has been included in the later investigation, and the results render it possible to form a gradation among the arc and spark lines of these elements according to the degree in which they respond to an excitation which is clearly favorable to the production of spark lines. Some light is also thrown on the probable character of the radiation produced in this way.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 73.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 65; *Astrophysical Journal*, **37**, 119, 1913.

DESCRIPTION OF EXPERIMENTS

Following the preliminary experiments already reported, the same method was employed at first to examine the spectra of different elements and to cover a greater range of wave-length. The vertical plane-grating spectrograph was used as before, with an objective of 30 ft. (9.1 m) focal length. An image of the interior of the furnace tube was projected on the slit, so that the latter passed across the horizontal diameter of the tube's image. The spectrum line photographed then registered the condition of the radiation for the given wave-length along this diameter. A number of second-order spectra for the region from λ 3850 to λ 4600, supplemented by some in the first order extending as far as λ 5400, confirmed the former results that the titanium enhanced lines maintained their strength with little change from center to wall of the tube, while the arc lines were strongest near the wall. The carbon spark lines at λ 3919 and λ 3921 (the former not given in the wave-length tables of Exner and Haschek, probably on account of its faintness) showed the same strength at the center of the tube and weakness near the wall which had been previously observed for λ 4267.

In the course of these experiments, a small spectrograph containing a concave grating of 1 meter radius was occasionally used to make photographs simultaneously with those of the large-scale instrument, the two windows at opposite ends of the furnace chamber being utilized in this way. These small-scale photographs showed the state of the tube-arc spectrum in the ultra-violet, but a fact of special interest was the appearance of the strong lines of hydrogen, in one case five members of the series from H_α to H_ϵ inclusive being photographed. The chief supply of hydrogen in this case was probably gas absorbed in the tube of Acheson graphite, since the air was pumped out to a pressure of less than 2 cm of mercury. The fact that the hydrogen spectrum appears thus in an arc at low voltage with high current is to be considered in connection with the other instances in which these lines have been observed in the arc, beginning with the experiment of Liveing and Dewar[1]

[1] *Proceedings of the Royal Society*, **35**, 74, 1883.

in which the hydrogen spectrum appeared when water was dropped into a carbon arc.

In order to examine the behavior of the hydrogen lines in different parts of the tube's cross-section, H_α was then photographed with the long slit of the plane-grating spectrograph along the horizontal diameter of the image of the tube, the first order of the grating being used. It was possible to connect the phenomena for H_α with those already observed for the tube-arc spectrum in the blue and violet on account of the presence of the carbon spark lines, $\lambda\lambda$ 6578 and 6583, close to H_α and a number of strong titanium arc lines in the same region. The experiments were carried out usually with a little titanium metal in the tube, though sometimes the tube was empty. In some cases the chamber contained air pumped to a low pressure, but stronger hydrogen lines were obtained when the furnace chamber was filled with purified hydrogen at from 2 to 5 cm pressure, the chamber being flushed at least three times with hydrogen before the tube-arc was operated. The intensity gradation of H_α from center to wall of the tube under these conditions proved to be the same as that of the adjacent carbon spark lines, the maximum intensity being at the center of the tube, with a gradual decrease toward the wall, agreeing perfectly with the appearance of the carbon spark lines in the blue and violet. It is the structure illustrated by the carbon line λ 4267 in the second plate of the previous paper. In striking contrast to these lines, the same plates showed a number of titanium arc lines having the usual structure observed in the tube-arc, weak in the center of the tube and strong near the wall.

An extended series of experiments was then taken up with the slit of the spectrograph along the vertical diameter of the image of the tube, which was of interest because the burning apart of the tube was often more violent at the bottom than at the top, especially when the tube was inclosed in the graphite jacket to be described later. I attribute this difference to the fact that the arc vapors from the top of the tube were carried upward into the cool space above, while the arc at the bottom of the tube had above it the hot vapor of the tube's interior. The conditions were thus favorable for a more violent vaporization of the carbon below than above,

and the effect of this appeared at once when the spectrograph was rotated so as to examine the state of the radiation along the vertical diameter of the tube. The maximum intensity for H_α and the carbon spark lines was now seen to be below the center of the tube, roughly one-third of the way between bottom and top. The intensity shaded off rapidly toward the bottom and slowly toward the top, the condition that the region near the wall is relatively unfavorable for these lines holding as for the observations along the horizontal diameter. The appearance of H_α and its neighboring carbon lines when photographed in this way is shown in Plate XI.

These experiments threw light on the effects previously obtained, showing that the maximum at the center of the horizontal diameter was due to its proximity to the true position of strongest radiation, situated slightly below the center. The standard appearance in the tube-arc was also given for lines which may be fairly considered as typical of spark radiation.

The next step in the investigation was the study of the arc and enhanced lines of a number of elements as given by the tube-arc, in order to compare the intensity distribution of such lines along the diameter of the tube with that of the hydrogen and carbon lines.

Attempts were made early in the work to obtain the magnesium spectrum, on account of the importance of the spark line λ 4481, but at first no trace of this line appeared, even with a large amount of magnesium in the middle portion of the tube. I could account for this only on the ground that since magnesium is very volatile, the intense heat in the thin part of the tube vaporized all of the metal present at the point where the break eventually occurred, and the vapor passed into cooler regions, so that when the tube burned apart the arc which formed did not contain enough of this vapor to show the spectrum in the short exposure. At any rate, the difficulty disappeared when magnesium vapor was supplied from without the tube, as was done by jacketing the middle portion of the furnace tube by a split graphite tube 10 cm long. When the latter was supported from beneath and the two halves placed together, it inclosed the thin portion of the furnace tube with a clearance of about 5 mm all around. A quantity of powdered magnesium was then placed in the jacket tube just below the place

where the arc would form, this being located by filing the tube still thinner at this point. This adaptation of the principle of the Moissan arc-furnace was effective. The intense heating of the furnace tube before burning apart served to vaporize the metal in the jacket tube, so that when the arc formed, the vapor in the jacket was ready to flow into the break. The magnesium spectrum then appeared with great brilliancy, λ 4481 being the strongest line in the blue region. Iron also gave a richer spectrum when some of the metal was placed in the jacket as well as in the tube.

The furnace tube with graphite jacket is shown in section in Fig. 1, the ends of the tube, which are clamped in vertical contact blocks, being omitted from the figure. The arc was made to

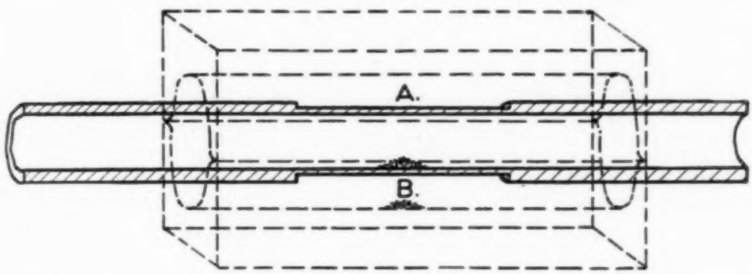


FIG. 1.—Arrangement of furnace tube and graphite jacket for tube-arc experiments.

form around the periphery of the tube at A B, the portion at B burning apart farther than at A. Aside from supplying vapor in the case of difficult metals, the jacket increased the difference between the burning at top and bottom of the tube, and seemed to enable the arc to hold longer than when no jacket was used. The duration of the arc varied greatly in different experiments. It usually burned from 5 to 15 seconds, which was quite sufficient for a strong photograph even with the large scale of spectrum used; but sometimes the arc ceased almost at once, and in one extreme case burned for 30 seconds. I have concluded from such modifications of the method as have been made thus far (the experiments being tedious on account of the labor of preparing the apparatus for each run) that in addition to a low pressure, tubes graphitized only to a certain degree give the best results for the

action of the tube-arc. Tubes of very smooth graphite did not hold the arc as well as those of which the material was somewhat gritty. Trials with carbon tubes have resulted in failures, but carbon can perhaps be made to serve if the required adjustment of size and impressed voltage are determined by extended tests.

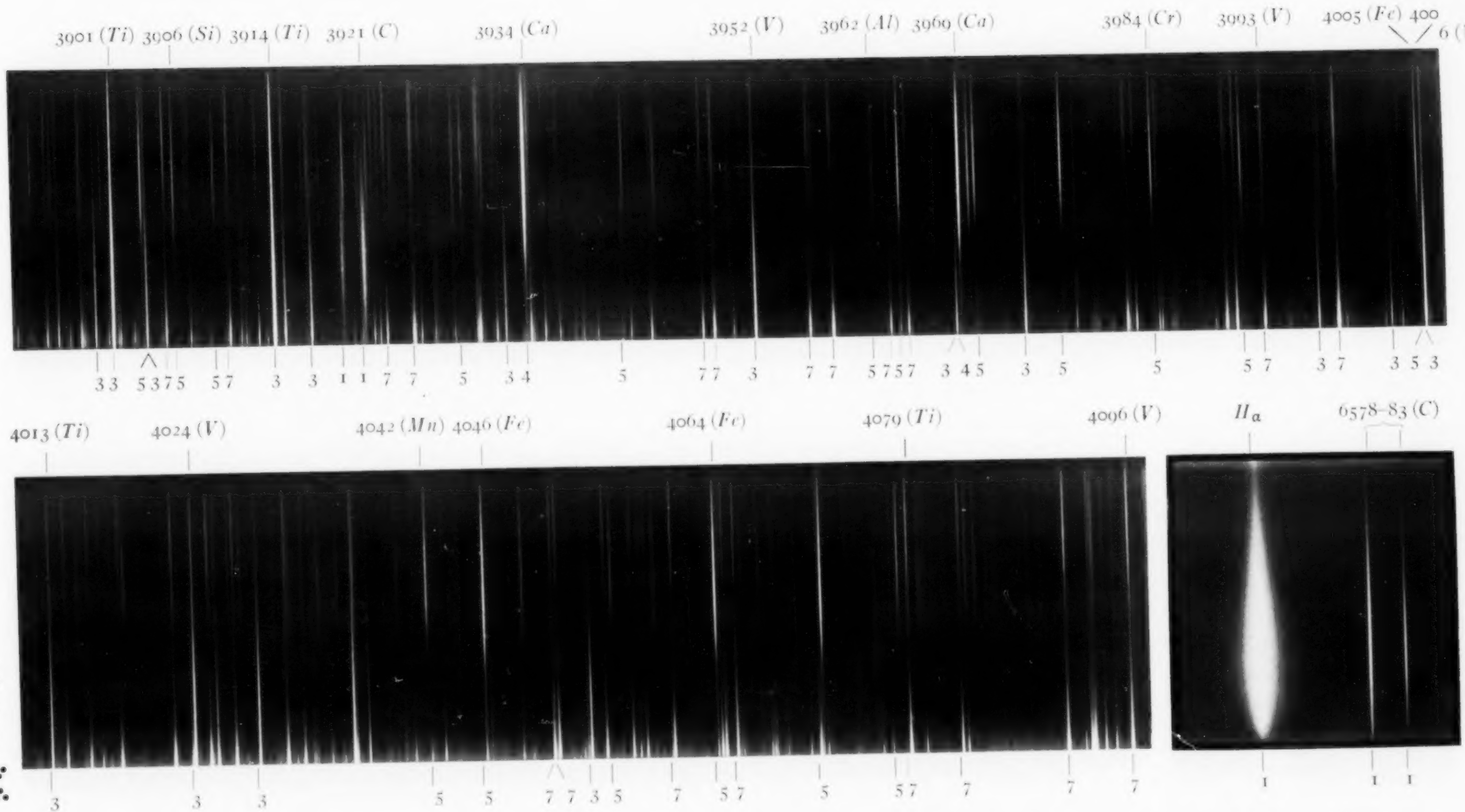
REGIONS OF SPECTRUM STUDIED

The results to be discussed are based on a set of fifty plates taken since those reported in the earlier paper. For about one-fourth of these, films were taken simultaneously with the 1-meter concave grating. Second order photographs were taken with the plane grating on a scale of approximately 0.9 Å per mm for the range from λ 3880 to λ 4280 and from λ 4240 to λ 4640. The carbon spark line λ 4267 occurred in both these sections and was useful for reference. An extended study was made of these regions and also of the first-order red including H_a. A few plates were made of the first-order green-yellow from λ 4800 to λ 5600, and two photographs were taken with the second order of the grating and an objective of 13 ft. (4 m) focal length. This gave greater brightness and nearly the same scale as the first order at 30 ft., the photographs being made chiefly to compare the behavior of λ 4481 of magnesium with the strong arc triplet $\lambda\lambda$ 3830, 3832, 3838.

GENERAL CHARACTER OF THE PHENOMENA

Photographs made with the spectrograph arranged so that the long slit passed along the vertical diameter of the image of the tube's interior present a very peculiar appearance, owing to the fact that different regions of the tube's cross-section are especially favorable for the production of certain groups of lines. The situation will be made clear by a reference to the spectra of Plates XI and XII, supplemented by the curves of Fig. 2. Plate XI shows, in two sections, a stretch of spectrum in the violet. Plate XII, *a* shows the relative behavior of the lines of several elements and especially the development of λ 4481 of magnesium. A number of typical lines of several elements are marked in the margin of each. In addition a reproduction is given in Plate XI of H_a and the adjacent carbon spark lines $\lambda\lambda$ 6578 and 6583, taken in the

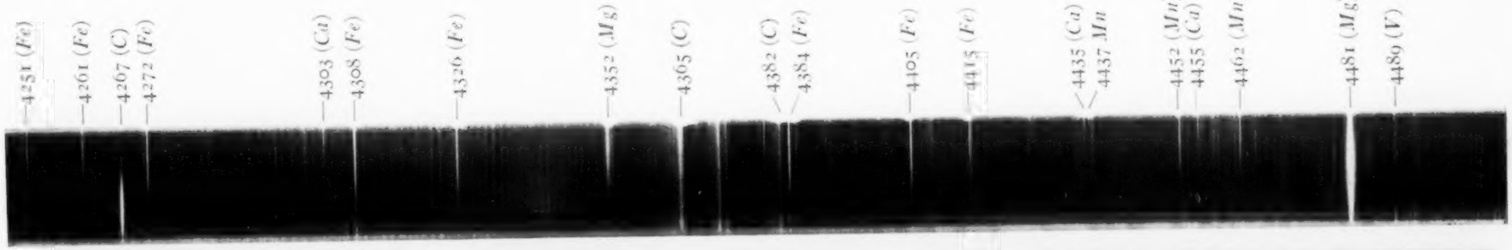
PLATE XI



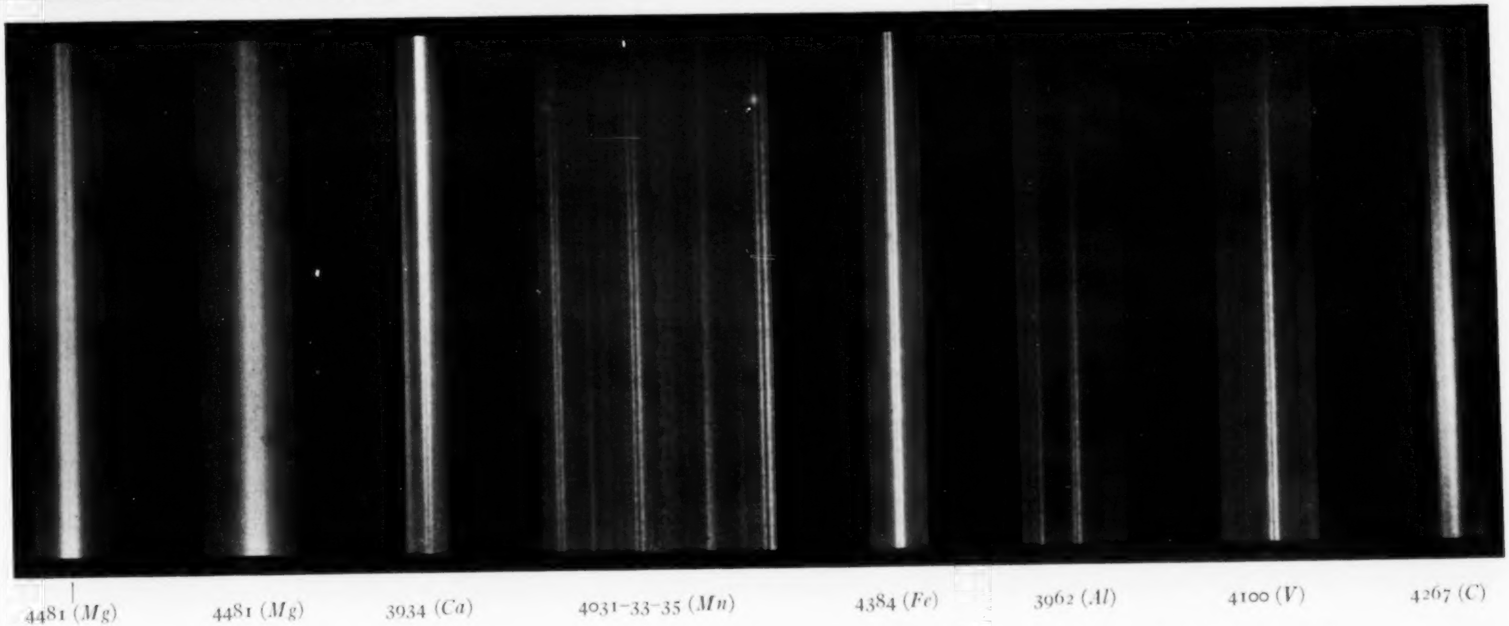
Spectrum of the tube-arc, with spectrograph slit along the vertical diameter of the tube's image, showing arc and enhanced lines of various metals, also lines of hydrogen and carbon. The numbers below refer to the groups on p. 323.

PLATE XII

a



b



a. Spectrum of the tube-arc, with spectrograph slit along the vertical diameter of the tube's image, showing the intensity gradation from center to wall of the tube of λ 4481 of magnesium compared with that of λ 4267 of carbon and of the arc lines of magnesium iron, manganese, calcium, and vanadium.

b. Enlargements of tube-arc lines, showing structure.

same way. The structure, as regards position of maximum strength, is seen to be the same for the hydrogen and carbon lines and the fact that the violet and blue carbon lines $\lambda\lambda$ 3919, 3921, and 4267 show their maxima at about the same height as those in the red establishes the form of this type of spark line. An attempt to represent this graphically is made in Fig. 2, the full-line curve from left to right following the intensity of the line from bottom to top, as given by the tube-arc. λ 4481 of magnesium shows its greatest intensity at about the same height as do the hydrogen and carbon lines, but weakens toward the wall of the tube above and below more slowly than these. The spark lines of lead, $\lambda\lambda$ 4245 and 4387, are similar. The gradation in intensity for these lines

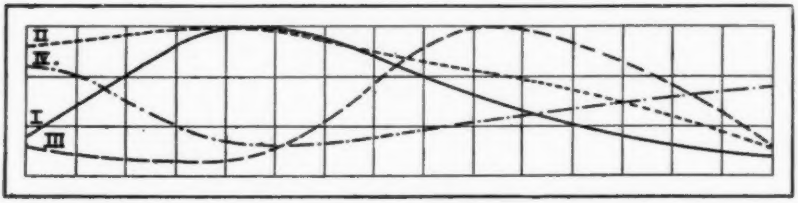


FIG. 2.—Curves showing intensity gradation of various groups of tube-arc lines from bottom (at left of figure) to top of the furnace tube. I, Groups 1, 2; II, Group 3; III, Groups 4, 5, 6; IV, Group 7.

is intermediate between that of the hydrogen and carbon lines and that of the enhanced lines of titanium, vanadium, iron, chromium, and manganese, which show a preference for the position which seems to be that of strongest spark radiation but are given with slightly diminished intensity at the bottom of the tube, where the arc burns with greatest intensity. The latter fade rapidly toward the top of the tube, the weaker lines of this class not showing in the upper half. Their intensity change is represented by Curve II. A distribution of intensity in strong contrast to the last class is shown by the arc lines of iron, chromium, magnesium, manganese, aluminum, calcium, strontium, barium, silicon (λ 3905.71), and tin (λ 4524.90). These lines are strongest slightly above the center of the tube. They weaken rapidly below the center, where the enhanced lines are strongest, and slowly toward the top of the tube (Curve III). The variability does not end here. The arc

lines of titanium and vanadium are distinctly in a class by themselves among the elements so far observed. Their maximum intensity follows the location of the strongest arc discharge, these lines being very strong at the bottom of the tube, weakest where the enhanced lines reach their maximum and increasing gradually to a strength at the top of the tube less than that at the bottom, a difference to be accounted for by the difference in the amount of burning of the tube below and above. (See Curve IV.)

By charging the tube with mixtures of various substances having important lines in the region under observation, it was a simple matter to unify the effects. Thus in the red, the spectra of hydrogen, carbon, titanium, iron, and calcium were obtained on the same plate. In the blue and violet, iron, titanium, and magnesium were frequently combined. The carbon spectrum was always given by the graphite tube. The addition of vanadium and chromium gave the behavior of these elements relatively to the others, while manganese, aluminum, calcium, strontium, barium, silicon, and lead lines appeared from impurities.

The intensity changes in lines from bottom to top of the tube, shown in the curves of Fig. 2, are estimated from typical lines on a number of good plates. The deviations from these intensity gradations were in degree rather than in kind. No approach to an inversion of the effect, such as the maximum of the carbon lines being above the center, or the titanium arc lines failing to weaken in the central portion, was ever observed. As has been noted, λ 4481 of magnesium extended with varying degrees of strength toward the top and bottom of the tube in different photographs. A combination of Curves I and II, with greater strength at the top of the tube than is given by either of them, would probably best represent its average behavior. On two or three plates, the enhanced lines of titanium inclined toward the appearance of the arc lines of that element, but remained relatively strong in the center of the tube, as compared with the arc lines. Deviations of this sort occurred in such a small percentage of the photographs that it was difficult to draw conclusions as to what conditions may have entered to produce them. It has been considered best to use only unreversed lines in judging the intensity variations in the

tube-arc. The region of strong emission is evidently greatly localized at the point where the tube burns through, but the condition of the absorbing vapors in the line of sight is uncertain, these being partly the cooler vapors from the arc and partly furnace vapors in the parts of the tube farther from the arcing portion. The conditions of emission and absorption may be quite different at a given point in the cross-section. However, lines of moderate strength which show no tendency to reverse in any part of their length may be taken as registering the conditions of emission at the part of the tube where the arc is passing.

While the curves of Fig. 2 illustrate the main differences for the lines of the elements studied, it is to be expected that minor differences will appear between elements which have been placed in the same class; and this is the case. By combining the spectra of several elements on the same plate, these small divergences given by the same experimental conditions may be detected and a sequence formed in which the substances are arranged in order according to their sensibility to conditions most favorable to lines strongly characteristic of the spark.

Such a sequence is given below, the elements which show the same behavior for their arc or spark lines, as the case may be, being grouped under the same number, with the numbers increasing according to the divergence from the most pronounced type of spark line.

1. Hydrogen lines (α, β, γ series)
   Spark lines of carbon
2. λ 4481 of magnesium
   Spark lines of lead
3. Enhanced lines of titanium, vanadium, iron, chromium, manganese
4. H and K lines of calcium
5. Arc lines of iron, chromium, manganese, magnesium, aluminum, silicon, tin
6. Arc lines of calcium, strontium, and barium
7. Arc lines of titanium and vanadium

These seven groups are approximately represented by the curves of Fig. 2 as follows:

Curve	I.	Groups	1, 2
"	II.	"	3
"	III.	"	4, 5, 6
"	IV.	"	7

The enhanced lines embraced in Groups 1, 2, and 3 have been described. The lines of Groups 4, 5, and 6 all have their maximum strength above the center of the tube, being relatively weak in the portion which gives the strongest spark lines. The lines H and K of calcium have their maximum strength nearer the center of the tube than do the arc lines of iron and similar elements, though the structure of H and K is rendered somewhat uncertain by their reversals. The reversal becomes narrower toward the center but the line is so much blacker in the negative at this portion that it seems fair to ascribe greater strength to the emission line.

Little difference is to be noted between iron, chromium, manganese, magnesium, aluminum, and silicon as to the structure of their arc lines, but the lines of all these substances retain their strength farther toward the center of the tube than do the arc lines of calcium, strontium, and barium. This was very distinct in photographs of the red region, where a number of strong lines of the latter elements were obtained on the same plates with iron arc lines. The difference between calcium and iron is shown by several lines on Plate XII, *a*. The carbon bands with heads at $\lambda\lambda$ 3884, 4216, and 4382 are strongest near the wall of the tube above and below. They retain their strength toward the center of the tube more in the upper half than in the lower.

All of the lines in Groups 1 to 6 inclusive show their greatest strength in some part of the tube away from the arcing wall. The region near the wall is not to be considered as really destructive to such lines, since every line, if made strong enough, is visible across the diameter of the tube; but certain parts of the cross-section are more favorable than others for a certain kind of line and the differentiation into groups is based on this characteristic.

In contrast to the foregoing groups, we have the arc lines of titanium and vanadium strongest near the wall of the tube, fading toward the part near the center where the enhanced lines of these and other elements are strongest.

Further, I have assured myself that the conditions which favor the various groups of lines exist, in the main, simultaneously. On several occasions, while an exposure with the large spectrograph was being made, the spectrum was observed visually through

the opposite window of the vacuum chamber by projecting an image of the tube's interior upon the (vertical) slit of a prism spectroscope. The appearance at any given moment was the same as that reproduced in Plates XI and XII, the varying strength of the lines in different parts of the tube being very striking. The carbon line λ 4267 (and presumably all of the weaker ones also) developed the greatest intensity shortly before the arc broke, at the time when all features of the tube-arc radiation should have their maximum effect.

DISSYMMETRY OF SPECTRUM LINES IN THE TUBE-ARC

In the previous paper, attention was called to the fact that the wider lines of titanium and λ 4267 of carbon become unsymmetrical in structure in the portion of the tube which gives the enhanced-line radiation most strongly. The later experiments have shown this phenomenon regularly, and have supplied data for the lines of several additional elements. The study of this feature of the tube-arc spectrum is still in a preliminary stage, as the effects have merely appeared incidentally on the plates taken primarily for the study of the intensity distribution in lines of various groups, but the material on hand is sufficient to show the general character of the effect and also the nature of the variations which occur.

If we have a line in the tube-arc spectrum showing partial or complete self-reversal, in most cases the red side of the line is the stronger. The effect is most decided in the part of the tube where the enhanced lines are strongest, and decreases toward the wall of the tube, the line often becoming quite symmetrical close to the wall. It was shown (see the third plate of the former paper) that this takes place only when the tube-arc forms, the same lines being quite symmetrical when given by the regular furnace with unbroken tube. This dissymmetry indicates that the emission line given by the tube-arc is slightly to the red of the absorption line due to the cooler vapors in the line of sight.

On the plates taken in the present investigation, fine examples of unsymmetrical reversal with the red side stronger are given by the more prominent iron arc lines in the blue and violet, notably $\lambda\lambda$ 3886.434, 4250.945, 4271.934, 4308.081, 4325.939, 4383.720,

4404.927, by the aluminum lines $\lambda\lambda$ 3944.160 and 3961.674, and by the strong titanium arc lines from λ 4513 to λ 4556 which were discussed in the former paper. The strong vanadium lines λ 4091 to λ 4135 are similar. This dissymmetry is always most pronounced near the center of the tube's cross-section, and the same lines appeared nearly or quite symmetrical in the spectrum of the ordinary arc photographed beside that of the tube-arc. A lesser degree of dissymmetry is shown by the titanium arc lines $\lambda\lambda$ 4298.828, 4300.732, and 4301.158. On plates for which the tube-arc conditions were apparently weaker than usual, these lines were almost symmetrical, while those above λ 4500 retained a certain amount of one-sidedness. λ 4352.083 of magnesium widens strongly toward the red, without reversal.

The H and K lines of calcium show almost symmetrical structure. The red side becomes slightly stronger near the middle of the tube, showing that, like the other lines, such dissymmetry as exists is most decided in that portion of the tube which gives the enhanced lines most strongly. This is in harmony with the observation by St. John[1] of the approximate constancy of the wave-lengths of H and K of calcium in various laboratory sources. The manganese lines $\lambda\lambda$ 4031, 4033, 4035 show no perceptible deviation from symmetry.

To sum up the situation in regard to dissymmetry, the evidence seems to leave no question that the intense excitation of the tube-arc gives a very decided effect of this sort, but no rule connecting the effect for different lines is as yet apparent. Most of the arc lines so far examined have their red side stronger but some show little or no effect. The hydrogen lines, carbon spark lines, and metallic enhanced lines, when not clearly double, appear very nearly symmetrical in the tube-arc. As was pointed out in the former paper, the condensed spark gives also a one-sided line, usually with the red side strongest. Perhaps it will be shown in general, as was observed by Kent[2] for three zinc lines, that this effect is due to satellites which are enhanced by the spark dis-

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 44; *Astrophysical Journal*, **31**, 143, 1910.

[2] *Proceedings American Academy of Sciences*, **48**, 91, 1912.

charge, thus changing the apparent position of the whole line when viewed with moderate dispersion. If this turns out to be the case, the varying effects of the tube-arc for different lines could result from satellites being enhanced on one side of the main line.

The tube-arc would scarcely be chosen to obtain lines for wave-length measurements, except in the case of those lines which can be produced by it better than by any other source, so that this tendency toward dissymmetry does not present a serious danger in measurements of laboratory spectra. In stellar atmospheres, however, conditions may often be present which closely approach those of the tube-arc, and a study from this point of view may explain many apparent anomalies in the positions of spectrum lines. A criterion as to when displacements of lines from this cause are to be expected would seem to be the prevalence of enhanced lines in the stellar spectrum in question.

THE STRUCTURE OF λ 4481 OF MAGNESIUM

An important feature of the spark line λ 4481 is brought out by the tube-arc photographs. The line appeared always *double*, the violet component being about twice as strong as the red. On most of the plates, the components were separated throughout their length. Other plates gave this line so strongly that the components blended photographically in the strongest part, while they were distinctly resolved at the ends. At first I considered the line as reversed and as an exception to the rule that tube-arc lines usually reverse with their strongest side toward the red. To decide this point the line was photographed on eleven plates, with the scale of 0.89 Å per mm, the intensities varying from the condition where the red component was barely visible up to a state much stronger than that shown in Plate XII, *a*. It was then clear that as long as the components were not so strong as to be blended, the interval between them was very nearly constant. This interval was measured by Miss Sheldon and the writer, a series of twenty determinations being obtained from the eleven plates, the interval being measured in some cases at the middle and at each end of the double line. The measurements, which covered large differences in intensity of the line, ranged from 0.20 Å to 0.23 Å, the majority

being close to 0.21 Å. This approximate constancy of the interval for such intensity variations, together with the fact that the components have the appearance of separate lines, rather than the well-known shaded and unsymmetrical appearance of the sides of a reversed line, offers strong evidence that λ 4481 is really a pair of enhanced lines, which appear to be affected in the same way by tube-arc conditions and presumably by those of the spark. A source in vacuum, either an arc or self-induction spark, combined with a large scale of spectrum, seems to be needed to give a good resolution of the components. The spark in air, even with much self-induction, does not give clear components. When weakened by this means so that the line is barely visible on the plate, it has the appearance of not being a simple line, the maximum being wide enough to contain the two components which the tube-arc shows. The wide line given by the condensed spark is well known to show dissymmetry toward the violet. The measured wave-lengths for this line in sources where it was made moderately narrow have shown much disagreement. Crew[1] and Hartmann,[2] among others, obtained large discordances in wave-length values when λ 4481 was measured on various plates given by the spark and rotating arc. The double structure shown by the tube-arc, combined with the greater strength of the violet component, would make its wave-length when unresolved depend largely on its intensity in the photograph in question, provided the component lines behave alike under varying physical conditions, which seems to be the case. The position of the apparent maximum will at first be that of the violet component when this alone is visible. When both are of moderate strength, the maximum will be between and near the violet component, moving gradually toward the red component as the violet member becomes overexposed.

The two components of λ 4481 have been measured on four plates with reference to $\lambda\lambda$ 4466.727 and 4494.738 (Rowland) of iron, the final values and their probable errors being as follows:

Violet component	4481.284 ± 0.0010
Red "	4481.499 ± 0.0012

[1] *Astrophysical Journal*, **16**, 246, 1902.

[2] *Physikalische Zeitschrift*, **4**, 427, 1903.

The carbon spark line λ 4267 also is shown by the tube-arc to be a doublet, the separation of the components measuring close to 0.26 Å with the red member rather more than twice as strong as the violet. This line was suspected by Hartmann[1] of being double, but I find no record of the components being resolved. The structure of the doublet has given rise to very discordant measurements of the wave-length by different observers. The wave-lengths of this and of other carbon lines given by the tube-arc will be published when large-scale photographs of the ultra-violet are obtained.

The lower portion of Plate XII presents enlargements of parts of several lines to illustrate their structure, including the magnesium and carbon doublets just discussed and a number of arc lines of which some remain symmetrical and others reverse with the red side strongest. The arc lines of calcium, manganese, iron, aluminum, and vanadium have in each case a portion enlarged from near the middle of their length, where the line is still strong, but is affected by the condition of strong enhanced-line radiation.

INVESTIGATION OF THE PROBABLE CAUSE OF THE TUBE-ARC PHENOMENA

The material thus far presented in this paper has been, like the first paper, simply a record of the experimental results. The classification of spectra which has been made is thus independent of any hypothesis as to the nature of the radiation processes involved. A full explanation of these processes would go far toward solving all questions as to the relation of arc and spark spectra. Some further data will now be presented which serve at least to narrow down the agencies which could bring about these effects.

The fact that enhanced lines in general are stronger in the tube-arc than in the ordinary arc in air is probably due largely to the reduced pressure. Few investigations have been made on the spectrum of the arc *in vacuo*, but such as have been carried out have shown that enhanced lines are strong in this source. Thus Fowler and Payn[2] found that λ 4481 appeared with great intensity in the carbon arc containing magnesium when inclosed in an exhausted

[1] *Astrophysical Journal*, **18**, 65, 1903.

[2] *Proceedings of the Royal Society*, **72**, 253, 1903.

vessel, though absent at atmospheric pressure; also that the enhanced lines of zinc and cadmium were prominent and the hydrogen line H_β sometimes appeared, probably from gas occluded by the electrodes. Barnes[1] also observed that λ 4481 is strong in a vacuum arc. Gale and Adams[2] found that the titanium enhanced lines are strengthened at reduced pressure. So far as the mere production of enhanced lines is concerned, the present observations on the tube-arc spectrum are to be regarded as additional data on the vacuum arc.

The unique feature of the tube-arc phenomena is the different behavior of the lines of different elements and of the arc and spark lines of the same element, as regards their intensity distribution over the cross-section of the tube. A question of the first importance is the relative temperatures of the vapor at the center of the tube and that near the wall. If the temperature is lower in the center, as would seem to follow if the arc follows the direct path between the ends of the broken tube, then the greater intensity of the enhanced and some of the arc lines away from the wall must be accounted for on other grounds. I have tried to picture a condition in which the temperature at the center might be higher. To be sure it is inclosed by a ring of arc, but experience teaches that the highest thermal condition in an arc is in the center of the path of the current, so that we must have the central vapor conducting as well or better than the graphite walls if the greatest current density is to be at the center. If this were true, we should be looking along the core of a powerful vacuum arc in these experiments. Such a conductivity for the central vapor would appear highly improbable and could conceivably result only from the great concentration of energy at the point of break, giving a very violent vaporization of carbon, which the experiments of Richardson and others have shown to give a high state of ionization.

I have carried out experiments to test this possibility. First an experiment of Harker and Kaye[3] was repeated. Two graphite

[1] *Astrophysical Journal*, **34**, 159, 1911.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

[3] *Proceedings of the Royal Society*, **86** A, 379, 1912.

rods, each of 6 mm diameter, were inserted at opposite ends of the furnace tube, which had an inside diameter of 12.5 mm. The rods, which were supported so as to be coaxial with the tube, were insulated from each other and from all parts of the furnace. The inner end of one rod was placed midway in the tube's length, so as to be in the hottest portion, the end of the other rod being near the end of the tube, in a relatively cool position, about 7.5 cm from the end of the first rod. Wires passed from each rod through an insulating plug in the head of the furnace chamber and to a direct-current ammeter. The tube was heated as usual by alternating current. When the chamber was pumped out and the tube heated to about 2600° C. at its central portion, the ammeter showed a direct current of about 1.5 ampere, varying only slightly on repeated trials. The cooler electrode was the positive one.[1] Although the phenomenon is somewhat complex, as Harker and Kaye have pointed out, it clearly gives us a current of considerable magnitude caused by the passage of negative corpuscles from the hot electrode to the cooler one. During one experiment, the tube burned apart at its middle, forming the tube-arc around the end of the inner electrode rod. The intense heating of the latter caused the ionization current to reach a value of 2 amperes.

The presence of a vigorous ionization being established, the next step was to measure the resistance of a column of heated vapor in the tube between the ends of two exploring electrodes and compare this with the resistance of the graphite tube itself. Two graphite rods similar to those used in the experiment just described were supported coaxially in the tube with their inner ends near the middle of the thin portion of the tube which was turned down for a length of 5 cm as in the tube-arc experiments. The ends of these exploring rods were 12 mm apart. The wires

[1] While the matter has no direct bearing on the present research, it may be noted here that a series of measurements was made at varying pressures, up to 20 atmospheres, keeping the apparatus as nearly as possible in the condition just described. A rapid decrease of ionization current with increasing pressure was observed up to 4 atmospheres (with compressed air) when 0.008 ampere was recorded. The fall in current values then became slower, and finally at 20 atmospheres, a current of 0.0015 ampere remained. While not enough check measures were taken to justify placing high weight on the values obtained, the general character of the change was brought out clearly, and it was evident also that even at high pressures the ionization is appreciable.

connected to them passed out of the furnace as before and were joined to a 6-volt battery with ammeter and a fixed resistance in series. The voltage across the electrode rods was read on a millivoltmeter which recorded a known fraction of the total voltage by means of a subdivided resistance. It was thus possible to take simultaneous readings of current and voltage at any stage after the vapor in the furnace tube had become conducting. Pyrometer readings of the tube temperature were made at the same time.

As soon as the tube became incandescent, a current appeared in the ammeter circuit, with corresponding reduction of the voltage across the electrodes. When the tube was heated to a state similar to that usually existing just before the formation of the tube-arc, the lowest resistance of the vapor between the electrodes, calculated from the current and voltage readings, was 1.1 ohm. This was with no metallic vapor in the tube except from impurities in the graphite. When a little titanium was put in the tube, the apparatus was in the same state as in many of the tube-arc experiments. The lowest resistance recorded with titanium vapor present was almost exactly 1 ohm. At the same time the resistance of the heating circuit of the furnace, which included the whole of the graphite tube and several contacts, was approximately 0.02 ohm. The current measured in the exploring circuit probably for the most part did not pass through the 12 mm of vapor between the ends of the electrodes, but leaked from each electrode to the wall of the tube about 3 mm distant. Even with such favorable conditions for the passage of a large current when the vapor in the tube becomes conducting, the resistance of this vapor is found to be large compared to that of the graphite wall.

The application of these results to the question as to whether the central vapors of the tube-arc can be regarded as the core of the arc, and thus as the region of the highest temperature, is that when the tube-arc forms, nearly all of the current must follow the shortest path between the ends, instead of curving through the central portion of the tube, about 6 mm distant. The view advanced in the former paper thus appears to be justified, that the enhanced lines are strong near the center of the tube in spite of the fact that the main path of the current is at the wall.

The arc lines of iron were expected to afford evidence as to the resemblance of different portions of the tube-arc to the core and flame of the ordinary arc, and, perhaps, by applying the data for intensity variations at different temperatures obtained by the writer[1] with the electric furnace, to indicate the nature of the temperature differences. It is well known that certain lines of iron are given chiefly by the outer vapors of the arc, others almost wholly by the core, while intermediate classes occur in both regions, being given most strongly by the intense radiation of the core. If corresponding variations exist in the tube-arc, a difference should appear in the position of the maximum strength of arc lines given by the long slit used in these experiments. The photographs show a very definite condition, though one scarcely to be expected. The "flame" lines of iron, strong in the outer vapors of the ordinary arc and relatively strong at the lower temperatures of the electric furnace (classes I A and I B of the furnace classification) are relatively weak in the tube-arc. Evidently no part of the cross-section gives a spectrum similar to that of the arc-flame, but neither is there evidence of strong core conditions. The relative intensities of a number of iron lines in the green-yellow afford a good test-spectrum for this purpose, a part of these lines being given almost entirely by the core. Such lines are only moderately strong in the tube-arc. The tube-arc spectrum, in fact, most closely resembles that given near the poles of the ordinary arc, on account of the relative strength of enhanced lines. A surprising feature is that no distinct difference is to be detected between the position of the maximum of a flame line which is barely visible in the tube-arc and that of a strong core line. At any rate, the difference is not as great as that between arc lines of iron and calcium, which results in the differentiation given on p. 323. The enhanced lines of iron, on the other hand, of which all of the stronger ones in the blue and green come out clearly in the tube-arc, show a distinctly different form, closely resembling the enhanced lines of titanium.

The only conclusion to be drawn from this test is that the radiation in all parts of the tube-arc is of a very intense character and

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 66; *Astrophysical Journal*, **37**, 239, 1913.

that differences in the arc lines which should result from a large temperature variation between center and wall do not appear.

The later experiments, with the slit along the vertical diameter of the image, do not point to differences in vapor density exerting a large influence. The supply of metallic vapor was always from below, whether the material was placed in the tube or in the jacket beneath. The region giving the strongest enhanced lines, while not in the lowest portion of the tube, is below the center, where a moderately high vapor density should prevail. If there is any large departure from uniformity in the vapor distribution, the region of least density should be above the center, and in this portion we find the arc lines at their strongest. As light sources in general do not show that a high vapor density is especially favorable to enhanced lines or that a rare condition is best for arc lines, it would seem probable that the vapor distribution is not a controlling agent in the tube-arc effects.

We may next consider the effect of a combination of thermo-luminescence and electro-luminescence, both of which must be active in this source, and whether the effects observed can be accounted for by a predominance of one or the other kind of radiation in a given portion of the tube. The distinction which modern theory makes between thermo- and electro-luminescence may be given briefly. In thermo-luminescence, the radiating vapor is highly heated, and the electron which imparts the light vibration to the ether derives its energy from the translatory motion and collisions of the heated molecules. Electro-luminescence, as exemplified in the discharge through vacuum tubes, does not require a heated state of the gas, but the energy of the light vibration is considered to arise from the impact of free corpuscles striking the vapor particles. To have a strong state of electro-luminescence in the tube-arc would thus require a plentiful supply of high-speed electrons bombarding the vapor. There can be no doubt that electrons in enormous quantities are shot off from the ring of intensely heated graphite where the arc forms. Their speed is probably much less than is attained with spark potentials, but they have as much velocity as a temperature generated by many kilowatts in the arc can give them, aided by the partial vacuum. The intense brilliancy of the hydrogen lines in the tube-arc

bears out the idea of a strong electro-luminescence, since that is the excitation which prevails in vacuum tubes, the source usually employed in the study of this spectrum. As regards the enhanced lines of metals, there seems to be no clear exception to the rule that a large potential gradient is needed for their appearance in the arc and spark. Thus in the continuous arc, if enhanced lines appear at all, they are close to the poles, where the potential fall is the most rapid. The interrupted and rotating arcs obviously give a strong potential gradient in the constantly recurring breaks, and the production of enhanced lines in such arcs has been ascribed to this feature. In the spark discharge, disruptiveness is recognized as an essential condition for strong enhanced lines. The analyses of the spark carried out by Hemsalech[1] and later by Schenck,[2] in which the separate oscillations were photographed by means of a rotating mirror, showed that the enhanced lines are due mainly to "streamers" projecting from the poles at the beginning of each spark. The electric field acting in these streamers should be much greater than that in the later oscillations which pass across the spark gap. The well-known effect of self-induction in weakening the enhanced lines was shown to be due to a damping of these initial oscillations, the chief energy of the discharge going into the later pulsations which the rotating mirror and spectrograph showed to radiate mainly arc lines.

The natural conclusion, which has been repeatedly expressed in substance by investigators of the arc and spark phenomena, is that large potential gradients in the arc and disruptiveness in the spark reduce in each case to a condition of high electronic speed, and that the lines peculiar to the spark are those which require this electro-luminescence, given by the impact of high speed corpuscles on the vapor particles. If this is recognized as the essential condition for the production of enhanced lines, it opens the way to account for their presence in sources where a high potential does not exist, and whose resemblance to the spark might seem, therefore, to be very slight. Thus it seems reasonable to the writer that a moderately strong state of electro-luminescence

[1] *Recherches expérimentales sur les spectres d'étincelles*, Dissertation, Paris, 1901.

[2] *Astrophysical Journal*, **14**, 116, 1901.

should be present in the tube-arc, resulting from the ejection of large quantities of electrons from the highly heated carbon, and that the strength of the enhanced lines, which in general is intermediate between that shown by the ordinary arc (near the poles) and by the condensed spark is to be accounted for in this way.

It remains then to account for the greater strength of the enhanced lines in the central part of the tube's cross-section, away from the wall which is the source of the supply of electrons. It is to be remembered that this is a relative condition, that the enhanced lines are given near the wall as well, so that the greater strength near the center would result through an increase in the number of electronic impacts which are occurring in some degree in all parts of the tube.

It may be that we need not look farther than the form of the tube for the cause of this strengthening. Electrons shot out normally to the heated surface should have the highest velocities, and the number of collisions with the vapor particles will obviously be greatest near the center of the tube. If the tube were placed vertically (an arrangement unfortunately not permitted by the present apparatus), a uniform burning of the arc around the circumference should take place, resulting in the location most favorable for enhanced lines being at the center. The more violent burning at the bottom of the tube, extending over about one-third of the circumference, would give a much greater supply of electrons emanating from this region, probably having somewhat higher velocities than those given by the weaker arc at the top, and the curvature of the wall would result in a greater number of impacts in unit time in the region below the center. The intensity distribution of the most typical spark lines, such as those of carbon and hydrogen, would then be explained. Enhanced lines such as those of titanium and iron, which appear in the ordinary arc, show only a slight diminution toward the bottom of the tube.

The radiation conditions in the region above the center of the tube are to be studied next, since an important class of arc lines is found to be strongest there. It would seem that the concentration (by virtue of the curvature of the wall) of the less numerous and probably slower electrons from the upper part of

the tube would give a radiation less intense than that below the center, but still having more of the qualities of electro-luminescence than the vapor close to the wall. The behavior of the enhanced lines is in harmony with this view, and it would mean that the arc lines of iron and several other elements respond more strongly to a moderate electro-luminescence than to the strong thermo-luminescence which probably prevails at the wall.

We could leave the phenomena of the tube-arc here, as being in the main accounted for by the concentration toward the center of the tube of the electronic bombardment, were it not that the arc lines of titanium and vanadium show a decided preference for the region near the wall. The distinguishing conditions at the wall are high temperature due to the proximity of the incandescent carbon, and probably fewer impacts by electrons than occur toward the center. If the first of these conditions governs the radiation of the titanium and vanadium arc lines, we have an interesting agreement with a peculiarity of electric furnace spectra, viz., that for titanium and vanadium the furnace at moderate temperature gives much more nearly a complete arc spectrum than it does for iron. The difficulty in producing a great many iron lines in the furnace which are strong in the arc was discussed in a paper[1] on this spectrum. With titanium and vanadium, the case is very different, in spite of the high melting point of these substances. Almost all lines shown by the arc, excepting enhanced lines, are given by the furnace at about 2400° C. Since the radiation of the furnace is probably as nearly thermal as any we have, while that of the arc is undoubtedly largely electrical, this is evidence that the vapors of titanium and vanadium respond to a condition of thermo-luminescence better than does the vapor of iron. In the tube-arc, granting a relatively strong state of thermo-luminescence near the wall, the observed behavior of the titanium and vanadium arc lines would be expected.

Referring to the curves of Fig. 2, the hypothesis just presented would make Curves I and II correspond to a state of high and Curve III to moderate electro-luminescence, while for Curve IV

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 66; *Astrophysical Journal*, **37**, 239, 1913.

thermo-luminescence predominates. The spark gives the strongest electro-luminescence and would be chosen to produce the enhanced lines of Curves I and II. The moderate electro-luminescence of the arc makes it the most efficient source for the lines of Curve III; while the thermo-luminescence of the furnace is sufficient to give almost complete spectra for the elements corresponding to Curve IV.

It is mainly because the recognized characteristics of spark, arc, and furnace spectra fit in so well with this hypothesis as to the varying strengths of electro- and thermo-luminescence in different parts of the tube-arc that I have felt justified in offering it. If the results obtained with the tube-arc are considered from this point of view, I find in them nothing that is anomalous or necessarily in contradiction with any recognized spectroscopic phenomena. Direct evidence as to the electrical state of the vapor is difficult to obtain, since the introduction of anything in the nature of an exploring electrode would modify by an unknown amount the regular conditions. I have, however, tried to alter the form of the tube to approach two parallel plates by cutting away opposite sides of the tube. When much of the material was thus removed, the arc would not hold, the inclosure of a large amount of carbon vapor before the formation of the arc seeming to be required. By reducing the size of the openings until holes about 3 mm in diameter above and below at the middle of the tube were left, I was able to get the tube-arc to act. The concentration of electronic impacts should have been somewhat reduced in this way. The H_α line was observed in particular, with hydrogen present at reduced pressure. The line, while still strongest at its middle, showed a nearer approach to uniformity throughout its length than when the regular tube without openings was employed. While this was the expected result, the experiment was not altogether conclusive, since the temperature and vapor distribution in the tube were altered by the openings.

Aside from the question as to why the enhanced lines are stronger near the center of the tube, their mere appearance in the vapor of a low-voltage arc is evidence either of a kind of excitation in this source similar to that which is regarded as an electro-

luminescence in the arc and spark, or of a temperature so high as to produce a light-energy usually imparted only by the impact of high-speed electrons.

The current in the tube-arc is very large, but the employment of high currents in an ordinary arc has never proved effective in producing enhanced lines. Hartmann[1] showed that very small currents are more favorable. Also, the evidence seems to be against a temperature increase in the part of the tube-arc which gives the enhanced lines most strongly. If the radiation be considered as probably due largely to the impact of electrons, evidently the temperature of the carbon which emits these electrons exerts a controlling influence. The phenomenon thus has a thermal basis, but the important difference from thermo-luminescence is that the vapor which emits the light need not itself be in a region of high temperature.

The amount of carbon present in a source emitting electrons is evidently highly important on account of the rich discharge of corpuscles from this substance. Thus, if two bodies are at the same temperature, but one of them contains more carbon than the other, the vapor in the vicinity of the one richer in carbon should give enhanced lines most strongly. It is doubtful, however, if a high percentage of carbon can compensate in any large degree for a deficiency in temperature; since it is the energy of the impacts, rather than their number, which determines the main features of the effect.

It is beyond the scope of this paper to take up the numerous applications which may be made in the field of astrophysics, the object of the work being to present in some detail the leading features of the spectrum of the tube-arc, and by a comparison with other sources to infer the probable character of its radiation.

SUMMARY OF RESULTS

The features of this investigation not covered in the former paper may be summarized as follows:

1. In the study of the tube-arc spectrum, a region near the center of the tube's cross-section has been found to give the

[1] *Astrophysical Journal*, **17**, 270, 1903.

hydrogen spectrum and the enhanced lines of metals most strongly, with some variation among different elements as to how rapidly their enhanced lines diminish in intensity toward the wall.

2. The arc lines of two groups of elements, represented by iron and calcium, show different degrees of response to the conditions most favorable for enhanced lines.

3. The arc lines of titanium and vanadium differ from those of the other elements studied, showing their greatest strength close to the wall.

4. Additional data have been obtained on the dissymmetry of lines produced in the central portion of the tube. While this is usually toward the red, some lines show little or no effect. The dissymmetry of λ 4481 of magnesium and of λ 4267 of carbon is explained by the observation that these lines are apparently double.

5. Tests have been carried out on the ionization of the vapor and on its conductivity compared to that of the tube material. The results of these, together with the spectroscopic phenomena of the tube-arc, indicate that the effects may be largely due to the impact of electrons emitted by the highly heated carbon, the resultant effect of these impacts becoming stronger near the center of the tube.

Mount Wilson Solar Observatory
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RADIAL MOTION IN SUN-SPOTS[1]

II. THE DISTRIBUTION OF THE ELEMENTS IN THE SOLAR ATMOSPHERE

By CHARLES E. ST. JOHN

In the previous paper on "Radial Motion in Sun-Spots"[2] the displacements at the peripheral edges of the spot penumbrae were given for some five hundred solar lines. The spots at the times of observation were between 25° and 60° from the center of the disk, and the slit of the spectograph was parallel to the radius of the solar image passing through the center of the spot umbra. The displacements were found to vary as the wave-length, and are interpreted as due to the Doppler effect arising from movements of the vapors of the reversing layer and chromosphere, tangential to the solar surface and radial to the axis of the spot vortex. The observations are in harmony with the explanation suggested by Evershed when he reported the existence of such displacements.[3] For convenience of reference in the course of the discussion, and to connect them with sun-spots by indicating their relation to the flow radial to the axis of the spot vortex, these displacements will be referred to as "radial displacements." For the purposes of discussion and comparison they have been reduced to the limb and to a common wave-length λ 5000, on the assumption that they are produced by movements of the solar vapors parallel to the solar surface. Displacements that indicate an outflow are called positive and displacements indicating inflow, negative. An increase of the displacements indicating outward flow with the decrease in the intensity of the lines of the reversing layer and the increase of the displacements indicating an inflow with the increase in the intensity of the chromospheric lines are striking aspects of the phenomena. The assumption is made that, on the whole, the lines of decreasing intensities are produced at increasing depths, and

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 74.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 69; *Astrophysical Journal*, **37**, 322, 1913.

[3] *Kodaikanal Observatory Bulletin*, No. 15, 1909.

therefore the direction and the speed of the flow may be considered a function of the depth. The displacements vary from large positive values for the lines of very low solar intensity to large negative values for the strongest calcium and hydrogen lines, and pass through zero values in the case of the strongest lines of aluminum and iron. The series of displacements for the iron lines of intensities 00 to 10, when arranged in the order of increasing intensities

TABLE I

IRON SCALE. DISPLACEMENTS REDUCED TO λ 5000 AND EXPRESSED IN ÅNGSTRÖMS

Intensity	00	0	1	2	3	4	5	6	7	8	10
Displacements	0.034	0.030	0.028	0.025	0.023	0.021	0.019	0.016	0.012	0.009	0.004
Vel. km/sec	2.04	1.80	1.68	1.50	1.38	1.26	1.14	0.96	0.72	0.54	0.24

Mean interval per unit intensity = 0.0026 Å = 0.16 km/sec.

TABLE II

DISPLACEMENTS IN ÅNGSTRÖMS OF STRONG LINES (λ 5000)

	Element						
	Mg	*Si*	*Al*	*Fe*	*Sr*	*Ca* λ 4227	H_δ
Intensity	10	12	15–20	15–40	20	40	40
Displacements	+0.002	0.000	0.000	0.000	−0.002	−0.002	−0.005
Vel. km/sec	+0.12	0.00	0.00	0.00	−0.12	−0.12	−0.30

	Element					
	Na D_1, D_2	*Mg* b_2, b_1	H_γ	*Ca* H_2, K_2	H_α	*Ca* H_3, K_3
Intensity	20, 30	20, 30	20		40	
Displacements	−0.012	−0.012	−0.033	−0.044	−0.050	−0.063
Vel. km/sec	−0.72	−0.72	−1.98	−2.64	−3.00	−3.78

of the lines, shows the march of the phenomena and also forms a scale with which to compare the displacements of lines of other elements of like intensities. It is deduced from the displacements of some 200 iron lines of intensities 00 to 10—all that were observed between these intensities—and represents a general mean into which the influence of the different groups of iron lines and of the different spectral regions enter in varying proportion.

Displacements throughout the paper are the relative displacements at the two edges of the penumbra, so that the displacements and the velocities are to be divided by two to obtain the absolute values.

For lines stronger than 10, the displacements are either very small or negative, and, in the latter instance, they increase numerically with the elevation; that is, they are greatest for what are known to be high-level lines.

The lines of Table II are in the main as characteristic of the chromosphere as those of Table I are of the reversing layer. The neutral region, the level of zero velocity, corresponds to the usual line of division between the reversing layer and the chromosphere, and seems to offer another ground for the customary division.

THE CHART OF DISTRIBUTION

When the displacements of the lines of different elements are compared, it appears that the displacements of the lines of like intensity differ. With the iron scale (Table I) established, it is possible to determine the relative levels in terms of this scale at which the lines of other elements are produced. A comparison for the violet region is shown in Table III for the lines of titanium, lanthanum, and cerium, where their displacements are compared with those of iron lines of the same intensity and in the same spectral region.

TABLE III

Comparative Displacements of Lines of Equal Intensity

Intensity	*Fe*	*Ti–Fe*	*La–Fe*	*Ce–Fe*
1	0.0264	−0.0021	+0.0026	+0.0066
2	.0240	− .0030	+ .0033	....
3	.0186	− .0020	+0.0070	+0.0074
4	.0181	− .0041	....	....
5	0.0166	−0.0041	....	....
Weighted mean	....	−0.0026	+0.0033	+0.0070
Levels referred to iron	....	1 unit above	1.3 units below	2.7 units below

The titanium lines are consistently displaced less than the iron lines, indicating that the former originate at a higher level; and the

lines of lanthanum and cerium are as consistently displaced more than the iron lines; hence the origin of these lines is assigned to a lower level than that of the lines of iron of the same intensity.

The relative levels of the lines of 26 elements have been determined by comparing the displacements of their lines with those of the lines of iron of equal intensity and in the same spectral region. The relative levels of the absorbing regions to which the various lines owe their origin are indicated in the chart (Fig. 1). In the case of iron, the displacements are entered in the diagram for each intensity. In the vertical columns the figures in the small rectangles indicate the intensities of the lines, and the position of the rectangles the corresponding levels; the figures in circles refer to the lines of the element stronger than any measured upon these plates; for lines stronger than 10 the actual displacements are given reduced to λ 5000. The absolute velocity may be found from the displacements by multiplying by 30. The vertical scale is entirely arbitrary. From 000 to 8 the ordinates vary as the intensities; one division of the scale corresponds to one unit of intensity and equals 0.0026 Å. For stronger lines the relative levels indicated are proportional to the actual displacements, and one scale division equals 0.0075 Å.

In speaking of the level at which a given line originates, it is to be borne in mind that this is not sharply bounded, but that some portion of the whole depth of the gas is more effective than all the rest in the production of the line. From the point of view that no light from the continuous spectrum background appears in the Fraunhofer lines and that their relative intensities depend upon the light in the lines emitted by the gases, it is evident that light of the wave-length considered, coming from the lowest depths from which it can reach the surface, emerges greatly reduced by absorption and scattering; that light from the lesser depths is greatly weakened because of lower temperature; and that it is the region between these two extremes that may be considered the effective layer.[1] If it be considered that the Fraunhofer lines are formed by partial absorption and that their intensities depend in large measure upon the light of the corresponding wave-length transmitted

[1] Abbot, *The Sun*, pp. 251–252, 1911.

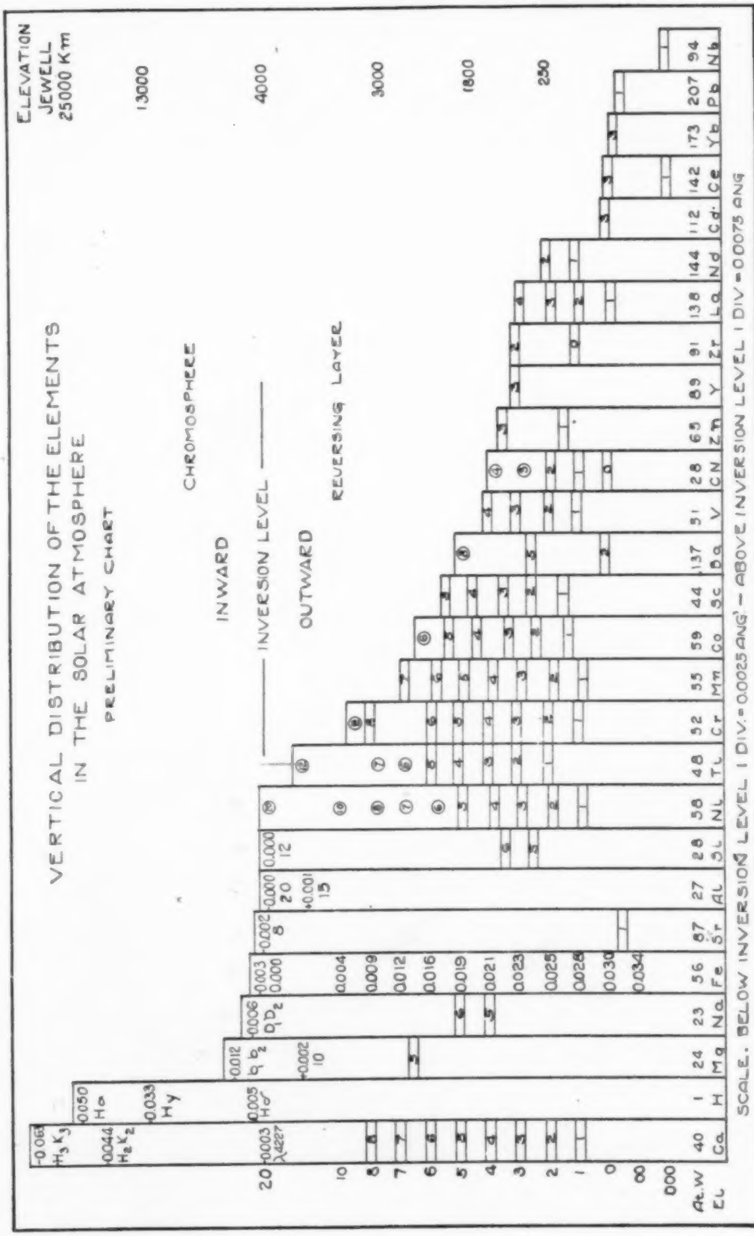

VERTICAL DISTRIBUTION OF THE ELEMENTS
IN THE SOLAR ATMOSPHERE
PRELIMINARY CHART
CHROMOSPHERE
INWARD
INVERSION LEVEL
OUTWARD
REVERSING LAYER
ELEVATION
JEWELL
25000 Km
13000
4000
3000
1800
250
SCALE. BELOW INVERSION LEVEL 1 DIV. = 0.0025 ANG. – ABOVE INVERSION LEVEL 1 DIV. = 0.0075 ANG
At. W
El.
40 Ca
1 H
24 Mg
23 Na
56 Fe
87 Sr
27 Al
28 Si
58 Ni
48 Ti
52 Cr
55 Mn
59 Co
44 Sc
137 Ba
51 V
28 CN
65 Zn
89 Y
91 Zr
138 La
144 Nd
112 Cd
142 Ce
173 Yb
207 Pb
94 Nb

FIG. 1

from the background, it is evident that the lowest regions having nearly the temperature of the photosphere would have small absorptive effect; that the upper limits of the gas are extremely rare and would, for most lines, produce little absorption; and that the main absorption would be due to the intermediate or effective layers, the level of which depends upon the selective absorption in the lines considered.

It will be noticed at once that high atomic weights are more numerous toward the right of the chart, pointing to a low level even for the strongest lines of the heavier elements. This becomes more evident when the atomic weights are taken in groups from left to right. Placing seven elements in the first group, and five in each of the others, we have from left to right:

	Group				
	1	2	3	4	5
Total atomic weight....	258	241	319	527	728
Mean atomic weight....	37	48	64	105	146

The upper limit at which the vapor of any element may be spectroscopically detected depends upon the strength of its lines; the stronger the lines the higher the level at which they can be detected. It might be thought that, if all elements had lines of equal intensities in the solar spectrum, the substances would be detected at equally high levels. But on the chart it will be noticed that the lines of the heavy elements, such as barium, lanthanum, neodymium, cadmium, cerium, lead, and ytterbium, originate at lower levels than the lines of like intensity of iron, and it might well follow that lines of these elements of greater intensity than those measured would also originate below the levels of the iron lines of equal intensity.

There are some interesting exceptions to the general tenor of the chart. The high level of calcium as shown by the H and K lines stands out as strikingly on the chart as in eclipse spectra and remains still an enigma. Cyanogen appears far to the right of iron, and strontium reaches a level higher than several elements of lesser atomic weight. The effect of the presence of metallic vapors

in the arc upon the lines of cyanogen or carbon is well known to be the almost complete extinction of the cyanogen lines, and it appears that the same conditions probably obtain in the gases of the solar atmosphere. The strong line of strontium λ 4077 is remarkably prominent in flash spectra; it is also enormously enhanced in the spark, and enhanced lines are at higher levels than unenhanced lines; that is, they show smaller radial displacements than unenhanced lines of the same solar intensity. It is to be remarked also that the strontium line λ 4161, intensity 1, originates at a much lower level than iron lines of the same intensity—shown by consistent measurements on 13 plates—so that the placing of strontium so far to the left in the chart depends upon the high level reached by what seems an exceptional line, while the level of the weaker line would place it farther to the right where its atomic weight would fall into the general scheme. The elements grouped around strontium in the chart differ but slightly in the levels given by their strongest lines. Their arrangement is therefore very uncertain and liable to change with additional data. The lines of intensities 5 and 6 assigned to silicon, which point to a low level for this element, are of interest in that λ 5948, intensity 6, was identified by Rowland as silicon; but it has never been observed since in the spectrum of this element, and its origin is doubtful.[1] Its relative position depends upon the measurement of 24 plates. The low level assigned points to the possibility of its being a line of one of the rare earth elements present as an impurity in the sample used for the identification by Rowland, or to its being a blend. Nothing is known of the source of the silicon that Rowland used. The line λ 4103, intensity 5, is a blend of silicon and manganese. The components would each be of lesser intensity, and their displacements correspondingly greater than in the case of a single line of intensity 5. In the complete list of lines observed appearing in *Contributions from the Mount Wilson Solar Observatory*, No. 69, there are 8 blends of mean intensity 4. The mean displacement of these lines is 0.024 Å, while the mean for other lines of the same elements and of equal intensity is 0.018 Å, indicating that the blends are at the level of lines of one-half their intensity. The

[1] Kayser, *Handbuch der Spectroscopie*, **6**, 482, 1912.

element niobium appears farther to the right than its atomic weight would seem to place it; but from the scarcity of the metal in the earth, one would be justified in believing that it and other rare earth metals form a very small part of the accessible solar atmosphere and are confined to a low level.

Taken by and large the spectroscopically determined levels may be considered to represent the approximate state of things. Much fuller laboratory data are greatly needed upon such points as follows: in the case of iron, nickel, and cobalt, for example, what are the relative intensities of the lines when produced under like conditions of excitation, temperature, and density? What changes occur when present in a mixture? The estimation of the intensities of the lines in the spectra of the elements is a very arbitrary matter. It would be of great service if some workable standard were devised, such, for example, as the iron arc under fixed conditions, and if it were possible to say even approximately how the lines of an element compare in intensity with certain lines of iron under similar conditions of density and temperature. The nearer the comparisons approach a quantitative basis the more valuable they would be. The electric furnace is capable of yielding a large mass of valuable data, as King has shown in the case of calcium and iron.

SPECIAL GROUPS AND REGIONS

In obtaining the mean displacement of the lines of a given intensity of any element, no consideration has been given thus far to the characteristics of individual lines or of the lines belonging to any particular group. In the paper on "Radial Motion in Sun-Spots, I" a comparison was made between lines in the violet and red for lines of equal solar intensity. From this comparison, it appeared that the lines in the red gave displacements about 0.005 Å greater than those of the same intensity in the violet, thus indicating a level for the lines in the red about two intensities lower than for lines of like intensity in the violet.

The original observing program contained a large number of enhanced lines, but they were not indicated as such in the working lists. It was the custom to select the lines that seemed best

adapted to measurement, when they were numerous enough to offer a chance for selection as in the case of iron, titanium, chromium, and nickel. When the data were finally assembled it was found that the enhanced lines had nearly all been eliminated by a kind of natural selection, which tends to show that they are more difficult to measure than other lines of the same elements and is a further indication that they form a distinct class. Blends aside, there are fourteen enhanced lines in the list for which comparisons with other lines of like intensity of the same elements are possible. The displacements of these lines are less than for the corresponding lines of the same elements, and point to a level for the enhanced lines higher than for unenhanced lines of like solar intensity; and there is some ground for thinking that the difference in level increases with the degree of enhancement.

TABLE IV

RELATIVE DISPLACEMENTS OF THE ENHANCED LINES

Elements	Intensities	Enhanced − Unenhanced	No. of Lines
Ti, Fe, Cr, Ni	2	−0.0033	9
Ti	3	−0.0046	4
Ti	4	−0.0021	1
Weighted mean		−0.0037	

As to the relatively high level indicated by the smaller radial displacements of enhanced lines, this seems explicable from the behavior of enhanced lines in spots. Mr. Adams has given the results for the known enhanced lines—144 lines—in his paper.[1] Of this number, 130 are weakened and none are strengthened in spots. It is also clear from Mr. Adams' summary that the percentage of weakening increases as the lines decrease in intensity, since the absolute change expressed in intensity units is approximately the same for lines of all intensities; lines of solar intensity 0–2, 3–4, and 5–6 are decreased by 1.3, 1.4, and 1.4 units, respectively.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 40; *Astrophysical Journal*, **30**, 86, 1909.

It has generally been considered that high temperature is a condition for the production of enhanced lines. From this point of view, the lessened intensity in spot spectra of enhanced lines produced throughout the reversing layer may be attributed to the lower temperature in spots. The weakening is greatest for low-level lines, which points to decreasing temperature as one approaches the levels in which these lines originate. In the case of any particular line, the lessened temperature of the lower portion of the layer effective in its production would tend to weaken the line and at the same time to raise its effective level by increasing the relative contribution of the upper portion of the layer. The changes of intensity are not confined to the spot umbra, but occur also in the penumbra, only less marked. The radial displacements refer to the peripheral edges of the penumbra, and the high level of the enhanced lines, relative to the level of other lines of the same solar intensity, may be a phenomenon peculiar to spots, and not indicative of a condition generally obtaining in the solar atmosphere.

The behavior of the enhanced lines under various conditions offers a fruitful field for investigation. They undoubtedly occur in flash spectra with greater relative intensity than other lines of a like solar intensity. Gale and Adams called attention to the great increase in relative intensity which the enhanced lines show in photographs of the titanium arc under reduced pressure.[1] This is a very marked phenomenon. Enhanced lines which under normal pressure are one-half the intensity of certain arc lines rise to double the intensity of these same lines when the pressure is lowered to 10 cm. Their suggestion that this change of relative intensity may have an application to the chromosphere is strengthened by the consideration that the Fraunhofer lines originate in rather definite levels. These levels are fixed by the mean depth at which the emergent light of the particular wave-length originates. At the edge of the solar disk the increased depth of the absorbing vapor raises the level from which light of a given wave-length can reach the surface; that is, we see into the sun to a less depth, so that the source of the lines in the flash spectrum is in

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 45, 1912.

a region of reduced pressure, and the relative intensities of the enhanced lines are increased.

The recent work by King upon the tube-arc spectrum of titanium in the electric furnace has shown that the enhanced lines may be relatively strong under conditions that seem not to depend directly upon temperature or great fall of potential. For a few seconds after the break of a furnace tube thinned in the central portion, the spectra, when the slit extends along the whole diameter of the tube, show the enhanced lines of titanium of nearly equal intensity from wall to wall, while the arc lines are strong near the walls but very weak in the axial portion of the tube. The conditions throughout the cross-section of the tube are equally favorable to the production of the enhanced lines of titanium, but relatively unfavorable for the production of the unenhanced lines in the axial region. The vapor producing these spectra is at the time surrounded by a wall of arc consuming approximately 24 kilowatts, supplied for a period of from 5 to 15 seconds under a potential fall not exceeding 33 volts. To the lower temperature of the axial region may be attributed, in part at least, the lessened intensity of the middle portions of the unenhanced lines. That the vapor density also may be less near the axis of the tube seems to be indicated by the behavior of the enhanced line of carbon, λ 4267—strong in the center and scarcely visible at the wall of the tube—as a high density of the other vapors near the wall would tend to obliterate it and a lessened density near the axis would be favorable to its production. If high temperature and low density are both favorable conditions for the production of enhanced lines, the effect of the fall of temperature toward the axis may be so nearly compensated by the effect of decrease in density that the enhanced lines may retain a nearly uniform intensity from wall to axis. The increased relative intensity of the enhanced lines under decreased pressure observed by Gale and Adams and by Barnes[1] is then a related phenomenon and the behavior of the enhanced lines in flash spectra would follow from the decreased density due to the higher elevation of the effective levels at the sun's limb.

Certain groups of iron lines based upon pressure displacements

[1] *Astrophysical Journal*, **34**, 163, 1911.

have been pointed out by Gale and Adams, namely, groups *b* and *d*.[1] To these have been added by Miss Ware and myself the groups *sub-d* and *e*. From a study of the eclipse results of Frost[2] and Mitchell[3] it appears that the lines of group *d* are at a higher elevation in the solar atmosphere than those of group *b*. The comparison, to be of force, should be between lines of the same intensity. Of 24 lines, mean intensity 5.3, belonging to group *b* present in the region included in the flash spectra, 75 per cent are present in the lists of Frost and Mitchell. Of 8 lines of mean intensity, 4.9, belonging to group *d*, 90 per cent are present, though the advantage of intensity is in favor of lines of group *b*. The spectral regions covered by the present investigation did not include regions where lines of groups *d* and *e* are most common. In Table V are given the residuals obtained by deducting from the displacements of the known lines of these three groups the means for all the iron lines of like solar intensity.

TABLE V

RESIDUALS

Intensity	Group *b* 24 Lines	Group *d* 9 Lines	Group *sub-d* 3 Lines	Group *e* 5 Lines
Fe 1	+0.0022 Å	....	....	−0.012 Å
Fe 3	+0.0025	....	−0.004 Å	....
Fe 4	+0.0003	+0.001 Å	−0.011	+0.004
Fe 5	+0.0039	−0.003	−0.010	−0.004
Fe 6	+0.0050	+0.001	....	....
Fe 7	+0.0003	0.000	....	....
Fe 8	+0.0010	−0.001	....	....
Mean	+0.0022	−0.0004	−0.008	−0.004

The comparison appears quite decisively to place the lines of groups *d*, *sub-d*, and *e* at higher levels than those of group *b*.

QUANTITY OF ABSORBING VAPOR

The thickness of the shells of vapor to which lines of different intensities of an element owe their origin is a rather surprising deduction from the chart of distribution and the elevations given

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

[2] *Astrophysical Journal*, **12**, 307, 1900.

[3] *Ibid.*, **15**, 97, 1902.

by Jewell. The iron lines of intensities 0000–10 are all below an elevation of 3500 km, giving an average thickness of 250 km for each intensity. For the lower levels, the average thickness is still less. The mean level of the shell of vapor in which the iron lines of mean intensity 2 originate is at an elevation of 250 km. As Jewell suggests: "The lower levels of the region of the chromosphere producing lines seen during totality are at least 200 or 300 and possibly 500 miles above the sun's surface. This will explain the absence of the smaller metallic lines in the flash spectrum."[1] Few lines of intensity 0 are reported by eclipse observers. In the lists examined there are only four of this intensity, so that the levels of lines of intensities 0000–0 would be within the 500 km of the sun's surface, corresponding to a thickness of some 125 km for each intensity.

The efficiency of the relatively thin shells of vapor in producing the Fraunhofer lines implies a greater quantity of vapor in the solar atmosphere than it has been customary to consider. From the small amounts that are effective in laboratory experiments in reversing the spectrum lines, it has been said that very minute quantities, thimblefuls, for example, were present in the sun's reversing layer. Very small quantities are effective for the lines of a given intensity for any element, but the absorbing centers effective for lines of different intensities of a given element are apparently not identical and appear to be allocated in successive spherical shells, so that the total quantity of any element, such as calcium, is much larger than necessary to produce any one line. Calcium is distributed throughout all levels. The weakest calcium line used in the present investigation is of intensity 1, and the pressure at the corresponding level probably exceeds 6 terrestrial atmospheres. An estimation of the quantity of calcium vapor in a column 1 cm square may be made, by assuming a reasonable proportion for the calcium content in the composition of the solar atmosphere at that level. Suppose it to be 1 per cent of the volume. The density of calcium is 40 times that of hydrogen. The partial pressure due to calcium vapor would be 60 g-dynes. The mass of the calcium content of the column $=60/27.6=2.18$ grams. The volume of

[1] *Publications U.S. Naval Observatory*, **4**, Pt. 4, App. I, 299, 1906.

this mass at 3000° C. and $P = 1$ atm. is 66.6×10^2 cc and is equivalent to a column 1 cm square and 67 m long, to be compared in absorbing power to the thin outer layer of calcium vapor in the arc. This quantity of calcium vapor in a vertical column of 1 square cm cross-section would mean, first, that complete absorption would probably occur for every line; second, that the light in a Fraunhofer line is due to the radiating vapor to which the line owes its origin; third, that the line appears dark because the temperature of the radiating layers are less than that of the source of the continuous background; and fourth, since the lower temperatures occur at the higher levels, that the lines originating in these levels show the strongest contrast with the background. This exposition of the formation of the Fraunhofer lines is that given by Abbot.[1] The great effectiveness of small amounts of vapor in producing reversals in the laboratory indicates that the effective layers in the sun's atmosphere need not be thick; and since the selective absorption varies directly with the intensity of a line, it follows that the effective layers would be at increasing elevations as the lines increase in intensity.

DISCUSSION OF RADIAL DISPLACEMENTS IN RELATION TO VARIOUS SOLAR PHENOMENA

The degree of dependence that can be placed upon the interpretation given in the present paper and the value of the results may be judged from the degree to which they harmonize with previously obtained data; from the manner in which they co-ordinate somewhat disconnected lines of solar work; from the additional light they throw on other investigations; and from the basis they furnish and the direction they indicate for further solar work. In the following sections the bearings of the results upon several lines of solar work will be discussed under the following headings: (1) radial displacements and eclipse results; (2) modification of spot lines as a function of level; (3) displacements at the sun's limb; (4) solar rotation and level; (5) magnetic field and level; (6) anomalous dispersion; (7) solar and terrestrial analogies.

1. *Radial displacements and eclipse results.*—In Table VI the lines for which Jewell[2] gives the elevations determined from the

[1] Abbot, *The Sun*, 1911.

[2] *Loc. cit.*

eclipse plates are arranged in groups, the lines in which are approximately at the same level according to the chart of the distribution of the elements. The enhanced lines, as has been shown, are at about the level of other lines of two intensities greater, and this is taken into account in the grouping of the lines. Lines for which the flash lines are plainly compound are not included, such as λ 4481. This is identified by Jewell with iron lines of intensities 5 and 3 and with a Fraunhofer line of intensity 0 which he assigns to magnesium. The identification of this weak solar line with magnesium is somewhat doubtful, as the magnesium line is very characteristic of the spectra of early type stars and probably disappears before the solar stage is reached.

TABLE VI

HEIGHT ABOVE SUN'S LIMB AND RADIAL DISPLACEMENTS

Intensity 1–3 Mean Int. 2	Intensity 4–6 Mean Int. 5	Intensity 7–15 Mean Int. 9	Near Level of Vel. Inver.	Intensity 40	Intensity —
200 *Ti* 100 *Ti*	800 *Ti* 900 *Ti*	3500 *Ti*	1500 *Ca*	8000 H_γ	15000 *Ca* K_3
100 *Cr* 150 *Zn*	600 *Fe* 1000 *Ti*	....	3500 *Sr*	....	....
200 *Y* 100 *Ca*	2500 *Ti* 1000 *Cr*	3000 *Ti*	....	....	....
100 *Ca* 150 *Ca*	1000 *Cr* 1000 *Cr*	1500 *Ba*	3000 *Mg*(*b*)	....	....
200 *Sr* 200 *Sc*	1000 *Fe* 1000 *Y*	800 *Fe*	1800 *Al*	....	....
200 *Fe* 100 *Mn*	....	1200 *Al*	....	....	....
150 *Cd* 150 *Zn*	....	1800 *Sc*	....	....	....
Means { 150 mi.	1080 miles	1970 miles	2450 miles	8000 miles	15000 miles
Means { 240 km	1740 km	3100 km	4000 km	13000 km	24000 km
Radial displacement +0.025 Å	+0.019 Å	+0.007 Å	−0.033 Å	−0.009 Å	−0.063 Å

From the comparison, it is very evident that large positive displacements are associated with low heights above the photosphere and large negative displacements with great heights, and that the general march of displacements follows the progression of heights for the intermediate elevations. It seems justifiable to draw the conclusion that the displacement of the Fraunhofer lines at the edges of the penumbrae of eccentrically located spots furnishes a method of sounding the solar atmosphere with considerable precision, a method of wide application and available whenever spots are on the solar surface.

In deducing the heights of levels from Jewell's paper the results

for one line were discarded. The line is λ 3694, of solar intensity 3, attributed by him to ytterbium and assigned a height of nearly 7000 km. If the displacements at the edges of the spot penumbrae are criteria of level, it would not be expected that this ytterbium line would reach so high a level in the solar atmosphere, since the level of its origin is near that of iron lines of intensity 00, and no lines of this intensity are reported by any of the five observers. In Jewell's report, the entry for this line is as follows:

Remarks	Chromosphere	Identification
Badly blurred	3694.4	3694.344 *Yb* 3

Possible identifications are, however, 3694.164, *Fe* 4, and 3695.194, *Fe* 5. Of the 37 lines of intensities 4 and 5 included in this investigation, 73 per cent are observed in the flash spectrum. It seems probable that the chromospheric line is not due to ytterbium alone but is coincident with the center of gravity of the three lines, which is at λ 3694.6, since the iron lines are not otherwise represented in this flash spectrum.

It is learned from Professor Campbell that there is a faint line at λ 3694.31 on the Lick Observatory plate of the eclipse of August 30, 1905. The small intensity of the line appears to negative an extremely great elevation for the same and to indicate that only a small amount of vapor is concerned in its production.

A comparison with eclipse results may be made by comparing the frequency of the appearance of a line in the flash spectrum with its radial displacement. On the assumption that radial displacements increase with depth, the more frequently occurring lines in eclipse spectra would show the smallest radial displacements. Such a comparison has been made with the eclipse results of Jewell,[1] Humphreys,[2] Frost,[3] Mitchell,[4] and Evershed.[5] From a comparison line by line through the region included by all the observers, the results are as follows:

Lines Observed by	Mean Radial Displacement
3 out of 5 observers	0.009 Å
1 or 2 out of 5	0.0023
None of the 5	0.0026

[1] *Publications U.S. Naval Observatory*, **4**, Pt. 4, App. I, 121, 1906.

[2] *Ibid.*, p. 252.

[3] *Astrophysical Journal*, **12**, 307, 1900.

[4] *Ibid.*, **15**, 97, 1902.

[5] *Philosophical Transactions*, **201** A, 457, 1903.

The results seem clearly in favor of the hypothesis that radial displacements are intimately connected with levels, and that the assumed variation with depth represents a real relationship.

In the preliminary report of the eclipse of August 1905 furnished to Abbot for his book *The Sun*, Mitchell says (p. 179): "It must be concluded that the flash spectrum is a reversal of the Fraunhofer spectrum, but with marked differences in the intensities of the two spectra." From the list of 92 lines in Mitchell's preliminary report, all lines not blends were selected for the comparison of the relative intensities in the two spectra. The results appear in Table VII, where the figures in parentheses give the number of lines involved. Lines of the heavy and rare elements, *Ba, Ce, La, Eu, Nd*, are used only in the right-hand end of the table.

TABLE VII

SOLAR AND FLASH INTENSITIES

	Elements									
	Fe, V, Co, Ti, Cr, Zr, ?							*Ba, Ce, La, Eu, Nd*		
Solar intensities.......	8	5	4	3	2	1	0	2	1	0–00
Flash intensities.......	5 (8)	2.5 (6)	1.5 (10)	2.8 (4)	1.5 (10)	0.6 (10)	0.8 (4)	2 (1)	4 (2)	1.8 (4)
Flash intensities$\times$1.6	8	4	2.4	4.5	2.4	1	1.3	3.2	6.4	2.9

In view of the excellence of the eclipse spectrum obtained by Mitchell, the comparison leaves no doubt of the changed relative intensities. The intensities in the flash spectrum multiplied by the factor 1.6 for better comparison are in the third line. The sum of the solar intensities in the first part of the table is 23. The sum of the flash intensities in the corresponding last line is 23.6, but the distribution of intensity is quite different. It is evident that lines of solar intensity 0 are relatively stronger in the flash spectrum, and for the lines of the heavy elements the increased relative intensity is most striking; the lines of cerium and lanthanum of solar intensity 0–00 are as strong in the flash spectrum as other lines of solar intensity 4. It thus appears that relative depths of the effective layers may be a determining factor in the increased brightness.

From the point of view that the lines of the heavy and rare elements originate in thin shells of vapor lying below the effective layers of iron lines of the same intensities, it is clear that large changes in relative intensities of the lines should occur in the flash spectrum; for let us consider the thin low-lying layer in which the cerium lines of intensity 0 have their source, and the higher level in which iron lines of intensity 4 are produced. The cerium Fraunhofer lines are weak because of the high temperature of the vapor; the Fraunhofer lines of intensity 4 having their source in the higher layer are stronger because of the lower temperature of the vapor. In the flash spectrum, consisting of bright lines, the higher temperature of the low-lying layer and the low temperature of the high layer are conditions that will increase the brightness of the lines of low origin in comparison with those of higher levels. Mr. Evershed suggests that the more extensively diffused gases would give the stronger lines in the flash spectrum by reason of their greater radiating areas.[1] This would be the result if the whole depth of the solar atmosphere were effective in the case of all lines due to a widely diffused substance, but the relatively greater brightness of the flash lines of the very low-lying layers of cerium giving solar lines 0–00 compared to the flash lines corresponding to lines of solar intensity 4 would imply that the region effective in producing the stronger Fraunhofer lines did not include at the limb the whole depth of the widely diffused vapors, but was comparable in thickness to that of the low-lying vapor of cerium. It may be assumed that the lower portion of the widely diffused vapor is coincident with and at the same temperature as the cerium vapor. If the whole depth of the widely diffused vapor were effective in producing the flash lines corresponding to the line of solar intensity 4, one would expect the flash lines due to it to be stronger than those due simply to low-lying vapors. As they are approximately equal in intensity, it would appear that only a portion, and not the lowest portion, of the widely diffused vapor was effective in producing either the flash lines or the Fraunhofer lines.

Since the above paragraph was written and just as the manuscript is ready for the press, some data from the unpublished results

[1] *Philosophical Transactions*, **197** A, 393, 1901.

of the Lick Observatory eclipse observations have been placed at the writer's disposal through the kindness of Professor Campbell. These refer to the eclipses of May 28, 1900, and August 30, 1905. In the latter case they include both the fixed and moving plate results. The increased relative intensity of the lanthanum lines appears here also. The mean solar intensity of the two lanthanum lines λ 4486 and λ 4123 is 1.5. The mean flash intensity is 2.1. As a basis of comparison the three strongest solar lines in this region may be conveniently used. The mean solar intensity of the cobalt line λ 4086 and of the two iron lines λ 4087 and λ 4123 is 3.7; their mean flash intensity is 1.4, so that the relative intensity of the lanthanum lines increases from 0.4 of the solar intensity of the comparison lines to 1.5 times the flash intensity of the same lines. Here, again, one seems constrained to conclude either that the thin low-lying layers of lanthanum vapor are more effective in producing bright lines than the whole thickness of the widely diffused iron vapor, including the very high-temperature portion coincident with the stratum of lanthanum vapor, or that only a portion of the iron vapor—the effective layer—is concerned in producing these iron lines, and that the comparison should be between the effect of the admittedly thin stratum of lanthanum vapor and that of the suggested effective layer of iron vapor comparable in thickness to that of lanthanum, as was done above in the case of cerium.

The same relatively great intensity of the reversals of the weak Fraunhofer lines is a very marked feature of the flash spectra photographed without an eclipse by Hale and Adams.[1] In their Table II covering the green region, 80 per cent of the identifications are with solar lines of intensities 000 and 0000 which are assigned to carbon or cyanogen. As has been pointed out, the effective level of the carbon or cyanogen lines given by the radial displacements is very low, and the conditions in this low layer of high temperature are particularly favorable to the production of strong bright-line spectra. The prevalence in these spectra of the reversals of the weak solar lines makes it probable

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 41; *Astrophysical Journal*, **30**, 222, 1909.

that Hale and Adams were observing at a lower level than that generally reached in eclipse observations, and lends additional weight to the interpretation based upon effective levels.

Some observations by Sir Norman Lockyer[1] upon the features of the flash spectrum taken at different elevations seem to bear directly upon the question of effective levels:

> In the spectrum taken very near the moment of second contact, representing that of lower strata with the spectra of the higher one superposed, the metallic arcs are relatively short and very bright, while in later photographs representing the spectra of successively higher strata free from admixture with lower ones, the metallic arcs are relatively feeble. This is also indicated in another way by the varying effects seen over the tops of lunar mountains and through indentations in the moon's limb. Some of the lines are seen to be much brighter in the upper strata than in the lower, such lines showing no increase in brightness at the points where lower strata are revealed through lunar valleys. Chief among these lines are those of hydrogen, helium, and calcium (H and K).

The relative brightness of the low-level metallic lines near the moment of contact, their weakening as successive portions of the solar atmosphere are covered by the moon, their behavior over the tops of the lunar mountains and in the intervening valleys, and the absence of increased brightness on the part of the high-level lines of calcium and hydrogen where lower regions of the solar atmosphere are revealed between the lunar mountains, all seem to limit the production of the lines to rather definite regions.

2. *Modification of spot lines as a function of level.*—In a paper summarizing the results of the study of the Mount Wilson sun-spot spectra,[2] Mr. Adams concludes that the weakening and strengthening of lines in the sun-spot spectrum may best be accounted for on the basis of a reduced temperature in spots. As the temperature would vary with elevation, the weakening and strengthening of the lines would be a function of level and bear a direct relation to their radial displacements. From the large amount of quantitative material in the paper referred to, the data respecting the character of the spot lines in Table VIII have been taken. In the last column are given the corresponding radial displacements.

[1] *Philosophical Transactions*, **197** A, 202, 1901.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 40; *Astrophysical Journal*, **30**, 86, 1909.

The H and K lines are difficult to classify, and by some observers have been considered as strengthened lines, since the central portion over spots appears generally brighter on the dark background of the wings. The apparent brightening, however, of the central portion is an effect of contrast due to the strengthened wings, as shown in a previous paper.[1] In the case of sodium D_1 and D_2, the wings are enormously strengthened. Unlike the H and K lines of calcium, the centers of D_1 and D_2 are simply the densest portions and are bounded by wings which are greatly strengthened and, as a result, widen the central portion on the two edges. The cores of

TABLE VIII

Lines	Character in Spots				Radial Displacement
Calcium H and K	Central portion weakened. Wings greatly strengthened				−0.063 Å
Hydrogen H_α	Weakened 40 to 25				− .050
Hydrogen H_γ	Greatly weakened 20 to 4				− .033
Hydrogen H_δ	Very greatly weakened 40 to 1				− .005
Magnesium b_1 and b_2	b_1 no change; b_2 slightly strengthened				− .012
Sodium D_1 and D_2	Cores widened; wings enormously strengthened				−0.006
	No. of Lines	No Change	Weakened	Strengthened	
Iron 10–30	9	67 per cent	33 per cent	0 per cent	0.000
Iron 5– 8	62	31	13	56	+ .015
Iron 2– 4	58	24	9	67	+ .024
Level of *Fe* 1 to *Fe* 000, weak *Ti* and *Na* lines	16	0	0	100	+ .031
Vanadium 00	2	0	0	100	+0.035

the lines, originating at the highest levels, upon which the measures of this paper are based, may still be unstrengthened or even weakened. As a whole, it is apparent from the table that weakening goes with high levels and strengthening increases with the depth. This is markedly true for the lines of moderate and low intensity, in which the proportion of strengthened lines increases and of weakened lines decreases systematically with the increase of radial displacements. As indicated above, the H and K lines of calcium and the D_1 and D_2 lines of sodium are probably not exceptions to

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 54, 29–31; also Plate III*a*; *Astrophysical Journal*, **34**, 131, 1911.

the general march of the phenomenon. When Mr. Adams' results for the lines of medium and low intensities of the other elements are considered, the same large percentage of strengthened lines is shown.

The weakening of the very strong lines follows from their origin in the high region where the cooling effect of the spot vortex has little effect on the temperature of the vapors and the lines are changed but slightly, if at all, in absolute intensity, but the continuous background against which they are seen is decreased in intensity so that by contrast they appear weakened.

In the case of hydrogen the weakening increases with the depth. Adams says:

> There is some evidence to indicate that the lines are most weakened in spots in which the bands and flutings are especially strong. If such is the case, it would tend to show that a large part of the hydrogen in spots goes to the formation of the hydride compounds, thus producing weakening of the hydrogen lines.

The hydride compounds are formed in the cooler regions of the umbra. The chemical action would spread upward and involve the lower levels of the overlying hydrogen more than the upper, thus reducing the intensities of the hydrogen lines in the inverse order of the elevations of their effective levels.

A cause working in the same direction is suggested by Abbot:[1]

> Owing to the lower temperature, the energy spectrum, that is the continuous spectrum background, in sun-spots as at the sun's limb, is weaker in the violet as compared with the red than is the ordinary solar spectrum. Thus, in spots, the radiation in the violet hydrogen lines approaches more nearly the brightness of the spectrum background than that in the red lines. Hence, the comparatively greater weakening of the shorter wave-length hydrogen sun-spot lines follows.

The general strengthening of the lines of the reversing layer results from the lower temperature in and directly above the spot umbrae, and the increased strengthening with depth indicates that the temperature decreases from the upper level to the lowest level accessible to the spectroscope.

The orderly march of the change of intensity of the lines in spots with the increase of depth of the corresponding lines in the

[1] *The Sun*, p. 269, 1911.

reversing layer at the edge of the penumbrae, indicated by the increasing radial displacements, points to the probability that the relative levels in the two cases are the same, that the absolute levels may not differ greatly, and that the lowest depths in sun-spots from which light affected by selective absorption reaches the surface of the sun is not greatly below the lowest levels of the reversing layer.

3. *Displacements at the sun's limb.*—From an extended investigation of the displacements of the spectrum lines at the sun's limb Mr. Adams concluded,[1] in agreement with Halm[2] and Fabry and Buisson,[3] that pressure is the determining factor in producing the displacements. It is of interest to consider such displacements from the point of view of the vertical distribution of the effective layers given by the data of the present paper. It appears that the effective levels are quite different for lines of different intensities, and are surprisingly shallow in the lower reversing layer and very thick in the upper chromosphere. Taking the elevations from Jewell's eclipse results, the lower levels are about 125 km thick on the average. The first 12 levels average about 250 km in thickness, while from the inversion level to H_γ it is 9000 km and from H_γ to K_3 it is 12000 km. If a given line originates in a comparatively thin shell, the path of light in the lower portions of the shell will be greatly lengthened at the limb; and if there is much difference in the pressures between the upper and lower levels of the shell, the line will have an increased wave-length and the increase will be on the red edge of the line. In the case of lines at very high levels the pressure throughout the shell is less than 1 atmosphere, so that the lines originating in these levels would show very small pressure displacements at the limb; and as the high-level vapors are descending over the general surface as shown for H and Mg and Na by Perot and Lindstedt,[4] and for Ca by St. John,[5] such

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 43; *Astrophysical Journal*, **31**, 30, 1910.

[2] *Astronomische Nachrichten*, **173**, 272, 1907.

[3] *Comptes rendus*, **148**, 174, 1909.

[4] *Comptes rendus*, **153**, 1367, 1911; **154**, 326, 1912.

[5] *Contributions from the Mount Wilson Solar Observatory*, No. 48; *Astrophysical Journal*, **32**, 36, 1910.

lines would show an apparent decrease in wave-length near the limb, or a small shift to the violet. In the case of lines at lower levels, the displacements toward larger wave-lengths should increase with lowness of level; but at very low levels where the differences in the pressure, and consequently the differences in density, between the upper and lower boundaries of the effective layers become large, the scattering of the light is greater and reduces the intensity from the lower portion of the effective levels; that is, the effective levels are higher than they would be without scattering. It follows that for very high levels the displacements should be negative, for lower levels positive and increasing, until a depth is reached in which the effect from scattering balances the increased effect from pressure and the displacements remain more nearly constant. At the lowest depths the cutting-off of the very deep-lying portion of the effective levels by scattering might well result in zero displacement, or even displacements to the violet or a complete obliteration of the line. In Table IX results for lines of different levels are shown. The levels are taken from the chart of vertical distribution, and under high and very high levels are included all the lines studied by Adams; under intensities 1 to 7 are included only the unenhanced lines of iron, and under the lowest level only the lines of barium, cerium, and lanthanum that according to the chart fall at this low level.

The figures in parentheses indicate the number of lines upon which the data are based. The march of the phenomenon is strikingly what would be expected. Mr. Adams also found that the displacements increased with wave-length. If the comparison be made between iron lines belonging to the same pressure group, *b* of iron for example, as can now be done since the work of Gale and Adams on the spectrum of iron under pressure through a wide range of wave-lengths, the agreement between the displacements at the limb and the pressure-shifts found in the laboratory shows with great clearness.

For 8 lines of intensity 5 near λ 4150 the displacement is 0.005 Å
" 5 " " " 5 " λ 6300 " " " 0.010

This shows more clearly still when the differences in level are taken into consideration, as lines in the red are about 1 intensity

TABLE IX

DISPLACEMENTS AT THE LIMB (ADAMS)

	Levels							
	Fe 0	*Fe* 1–2	*Fe* 3	*Fe* 4	*Fe* 5	*Fe* 6–7	*Fe* 8–20	Above Level of Inversion
Element...............	*Ba, Ce, La*	*Fe*	*Fe*	*Fe*	*Fe*	*Fe*	*Fe, Si, Ti*	*Al, Ca, H, Mg, Na*
Displacements..........	0.000 (10)	0.005 (18)	0.005 (20)	0.006 (21)	0.007 (20)	0.007 (28)	0.004 (16)	−0.002 (14)

below, and those in the violet about 1 intensity above, the mean level for lines of the same intensities. The lines at λ 4150 correspond to the general level of intensity 6, and those at λ 6300 to the level of intensity 4. So that, with no increase of displacement with wave-length, the displacements of lines of lesser wave-lengths to those of the larger wave-length would be in the ratio of 7:6 instead of 5:10, as they are, which indicates that between the displacement of λ 6300 and that of λ 4150 the real ratio is about 2.3:1. The pressure displacements in the case of iron lines vary as the cube of the wave-length, according to the results of Gale and Adams already referred to; hence between the wave-lengths considered the ratio between the pressure-shifts is 3.4:1. In view of the rise in the level of the effective layers near the limb due to scattering and selective absorption, which tends to reduce the displacements caused by pressure, unequally at different depths, only a qualitative agreement would be possible between the pressure-shifts in the laboratory and the displacements between center and limb.

When the displacements of the unenhanced lines of titanium are compared with those of iron at corresponding levels the ratio displacement of iron to displacement of titanium is 2.1:1. When displacements under pressure are compared it is 2.0:1.

Mr. Adams found that the enhanced lines gave larger displacements than the unenhanced. He discussed the suggestion made by Mr. Evershed that the enhanced lines are due to the ascending currents of hot gases represented by the granulations, but said:

> Another possible explanation of the larger displacements given by the enhanced lines must not, however, be overlooked. This is the possibility that the enhanced lines may show larger shifts under pressure in the laboratory.

Data are now available for a comparison between pressure-shifts in the laboratory and the displacements between limb and center for identical lines, by considering the lines common to the table of limb–center displacements given by Adams[1] and the list of pressure-shifts of titanium lines given by Gale and Adams.[2] Table X shows the results.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 43; *Astrophysical Journal*, **31**, 31, 1910.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

The practically identical ratio between pressure-shifts and displacements between limb and center points to an intimate relation between the two phenomena.

The result of the discussion from the point of view of this paper is that pressure can with great probability be assigned as the predominating factor in the phenomenon, and that the effect of pressure is modified by differences of level, is lessened by scattering in the lower levels, is entirely overcome at the lowest levels, and at the highest levels the general downward movement of the vapors masks or reverses the pressure effect.

TABLE X

ENHANCED AND UNENHANCED TITANIUM LINES

Lines Common to Both Lists	Displacements	
	8 Atmospheres	Limb–Center
17 enhanced.........	0.034 Å	0.0046 Å
36 unenhanced.......	0.023	0.0030
Ratio enh. to unenh..	1.48	1.53

4. *Solar rotation and level.*—The extended series of measurements made by Mr. Adams and Miss Lasby[1] furnishes a large amount of material for an investigation of level when considered in connection with the general results of this paper, which point to a mean level for the lines of the elements of a given intensity. In making the comparison between the two series of measurements, it is to be borne in mind that the results in the case of the solar rotation are based upon repeated measurements of the same lines, while the results of the present paper refer to groups of lines, and it is therefore to be expected that individual lines will occasionally depart from the mean results of a group. The differences between the results for different lines in the case of the rotation measurements, if the differences are real, mean that the displacements between the two limbs of the sun have been measured to the fourth decimal place. To obtain data of the maximum weight, the mean angular velocities for all latitudes from 0°–45° and from

[1] *Publications of the Carnegie Institution of Washington*, No. 138.

50°–80° have been formed in the case of each line. All the lines, 15 in number, that are common to both series given by Adams which are not blends are considered in the course of the comparison. In Table XI the lines used are grouped according to the levels indicated by radial displacements.

TABLE XI

ANGULAR VELOCITY OF SOLAR ROTATION AND RADIAL DISPLACEMENTS

Lat.	H_a	λ4227	*Fe* 3 (1)	*Fe* 2 (4)	*Fe* 1 (1)	*Cn* (1–2)	*La* 2
0°–45°	14°65	14°44	14°00	13°95	13°92	13°78	13°83
50 –80	14.39	13.93	11.72	11.70	11.68	11.48	11.36
Radial displacement	−0.050	−0.002	+0.019	+0.024	+0.026	+0.026	+0.028

The arrangement in order of depth given by radial displacements is the same as that given by the solar rotation values on the hypothesis that large negative values of radial displacements denote high elevations, that large positive values refer to low levels, and that the angular velocities increase with the elevation in the solar atmosphere. The lines of nickel and chromium are at the same general level as the lines of iron of the same intensity, and those of titanium are at a somewhat higher level. The results for these elements are in Table XII. For 12 out of the 15 lines the order

TABLE XII

ANGULAR VELOCITIES FOR LINES OF SAME LEVEL

Lat.	*Fe* 1	*Ni* 1	Mean	*Fe* 2	*Cr* 2	*Ti* 1	Mean
0°–45°.........	13°92	13°89	13°91	13°95	13°96	13°90	13°94
50 –80	11.68	11.70	11.69	11.70	11.70	11.72	11.71

of the levels given by the two investigations is in agreement. There remain three cases where the indications are contradictory. The enhanced line of titanium, λ4290 of intensity 2, gives rotation values that are consistently low, and the two lines of manganese, λ4257 and λ4266 of intensity 2, values that are consistently high. In Table XIII the rotation values of these lines are compared with those of *Fe* 2.

TABLE XIII

EXCEPTIONAL ANGULAR VELOCITIES

Lat.	*Mn* 2		*Fe* 2	*Ti* 2 λ 4290
	λ 4257	λ 4266		
0°–45°	14°04	14°00	13°95	13°85
50 –80	11.90	11.88	11.70	11.57
Radial displacements	+0.027	+0.028	+0.024	+0.015

These lines are in the violet region of the spectrum where the lines are closely packed, and it is never certain that a given line is not a blend. If the titanium line is a blend, its low rotation value would be explained, as the components of a line of intensity 2 would be at a very low level. As to the high level of this line indicated by the small radial displacement, this follows from the behavior of enhanced lines in spots. In the case of enhanced lines, as has been shown, the relative levels effective in radial displacements in spot penumbrae are probably not the same as those effective in solar rotation displacements, the effective layer being relatively higher in spots than in the general reversing layer. From this point of view, the low rotation value found by Adams and the small radial displacements shown are not inconsistent.

In the case of the manganese lines the difficulty caused by their higher angular velocity would be increased if they are blends, but the large radial displacements would be explained. The radial displacements depend upon only 6 or 7 plates, for which the mean deviations are much higher than the average. As has been said, the rotation values emphasize the character of an individual line, while, in the case of the radial displacements, the variation of a single line from the mean might well be accidental. There are a number of cases in which individual lines show large departures from the mean, but the data at present are too meager to establish a variation in the case of an individual line. In the 1908 series Mr. Adams added the line λ 4233, intensity 4, which Rowland attributes to *Mn-Fe*. It is conspicuous in eclipse spectra, but yields the same rotation value as the reversing layer which is based upon lines of intensity 2. If it is a blend of manganese and iron,

its components would be at the mean level of lines of intensity 2 and the agreement with the mean for the reversing layer would not be surprising. If one or both components are enhanced, its appearance in the flash spectrum would be expected from the effect upon the enhanced lines due to decrease of pressure following the rise in level of the effective layers just outside the border of the solar disk.

The value that Adams found for the reversing layer was determined from lines of mean intensity 2. As shown by radial displacements, there are lines suitable for rotation measures of still lower level than *La* 2, which gave the lowest angular velocity. For example:

La 1, displacement +0.029 Å at the level of *Fe* 0
Ba 2 and *Yb* 3, displacement +0.031 Å at the level of *Fe* 00
Nb 1, displacement +0.035 Å at the level of *Fe* 000

It is possible and quite probable that, if Mr. Adams had used these lines, he would have found a still lower angular velocity. There are some data for lines of higher level than *Fe* 2. In the 1908 series Mr. Adams added 2 calcium lines of intensity 4 to the observing list. Perot used 4 lines of mean intensity 7. Dunér and Halm both used the *Fe* lines λ 6301 and λ 6302 of intensities 7 and 4. Story and Wilson used 9 *Fe* lines of mean intensity 4, including λ 6301 and λ 6302. The comparison in the case of the two calcium lines of intensity 4 that Mr. Adams used in 1908 is made with the means of that series in which the mean intensity of the lines is 2, and shows in Table XIV.

TABLE XIV

ANGULAR VELOCITY AND INTENSITY

Lat.	*Ca* 4	Rev. Layer
0°–45°	13°99	13°98
50 –80	11.34	11.27
Radial displacements	+0.019	+0.024

The difference in angular velocity is slight and, if the case stood alone, it would be negligible and hardly deserve consideration; but the probability of its being real is strengthened when it is con-

sidered that, of the 13 latitudes, 3 only give negative results and the mean residual for the 13 latitudes is +0.03, and by the fact that it is in harmony with the more decisive cases given in this paper. Table XV gives the data for comparisons of Adams' results with those of Perot,[1] Dunér and Halm, and Story and Wilson. The mean of the two series of Mr. Adams are taken from Table 30, *Publications of the Carnegie Institution*, No. 138. The values for Dunér and Halm are those given by Pringsheim,[2] and the Story and Wilson values are from their paper.[3] The means of these three determinations are used for the comparison with the means of the two series by Mr. Adams and Miss Lasby.

TABLE XV

ANGULAR VELOCITIES FOR LINES AT DIFFERENT LEVELS

Lat.	Perot	Dunér	Halm	Story and Wilson	Mean Dunér, Halm, Story and Wilson	Adams and Lasby	Mean—Adams and Lasby
0°2....	14°8	14°8	14°6	14°8	14°7	14°5	+0°2
15.0....	....	14.5	14.3	14.5	14.4	14.3	+0.1
29.7....	....	13.9	13.7	14.0	13.9	13.7	+0.2
45.0....	13.2	12.8	13.2	13.3	13.1	12.8	+0.3
59.6....	....	11.5	12.6	12.4	12.2	11.9	+0.3
75.9....	....	10.7	12.3	11.2	11.4	11.3	+0.1
Intensities...	7	6	6	4	5.3	2	
Radial displacements.	+0.015	+0.018	+0.018	+0.021	+0.019	+0.024	

The lines are not all in the region of the spectrum covered by this investigation and the radial displacements indicated are for iron lines of equal intensities. The mean values found by Dunér, Halm, and Story and Wilson are of such weight that when they are compared with the results found by Adams and Miss Lasby the indications of higher levels in the case of these heavy iron lines are very strong. The angular velocities found by Perot, depending, however, upon much slenderer data, point in the same direction.

The comparison of solar rotation values with radial displacements indicates two methods at hand for determining the relative

[1] *Comptes rendus*, **147**, 340, 1908.

[2] *Physik der Sonne*, p. 60, 1910.

[3] *Monthly Notices*, **71**, 686, 1911.

levels in the solar atmosphere at which the Fraunhofer lines originate. The agreement between the results given by the displacements at the two edges of the penumbrae of spots due to motion of the vapors radial to the vortex axes and the displacements at the limb due to rotation indicate that the distribution in the neighborhood of sun-spots is, in general, the same as in the undisturbed regions of the solar atmosphere, and suggests a wider program for both methods of investigation. There is a great difference in the ease of application of the two ways of sounding the solar atmosphere. The differences in the angular velocities of the succeeding levels are difficult to establish by the displacements due to solar rotation. In the results of Mr. Adams the tangential velocities in latitude 45° for lanthanum and the reversing layer differ by 0.02 km per second. To detect this difference by determining the displacements between the east and west limbs of the sun requires measurements to 0.0006 Å. The radial displacements differ, however, by 0.0025 Å per unit intensity, so that measurements of differences of level by this means are well within the range of many instruments.

The bearing of the radial motion phenomena upon the question of level raised by the rotation values found from different lines and elements was not fully realized during this investigation, and appeared clearly only when the observations were finally reduced and the data assembled. The confirmation of the solar rotation results found by Mr. Adams and Miss Lasby coming from such an apparently unrelated investigation is of peculiar interest and importance in view of the negative results that follow from the solar rotation investigations of Hubrecht[1] and Plaskett and DeLury,[2] who observed no differences that they considered due to different elements and lines. If, however, the differences in radial displacements are rightly interpreted as indications of differences in level, certain differences in level appear to be established, for the radial displacements of the lines differ so greatly upon a given plate that exact measurement is not necessary to fix the fact of systematic differences in the direction and the amount of the displacements for lines differing sufficiently in intensity.

[1] *Monthly Notices*, **73**, 5, 1912.

[2] *Astrophysical Journal*, **37**, 73, 1913.

That a difference exists between the angular velocity of the high-level hydrogen and that of the reversing layer seems clearly shown by the accumulated observations. The values found spectrographically from the H_α line by Adams and Perot are respectively 15°0 and 15°2. From a long-enduring dark flocculus Evershed determined an angular velocity of 15°1, and from still richer observational material Deslandres and d'Azambuja obtained the value 15°0 for the absorption markings upon H_α spectroheliograms. The equatorial values found for the reversing layer are, Dunér 14°8, Halm 14°6, Adams 14°5, Story and Wilson 14°8, Hubrecht 13°2, Plaskett and DeLury 14°2. Since the lowest value determined from the H_α line is greater than the highest found for the reversing layer, the data seem to establish the existence of a difference in rotation associated with a wide difference in level and to make it probable that the differences that have been observed within narrower ranges of level are real. The small deviations in rotation results which Plaskett and DeLury are inclined to consider accidental or personal have in the large differences in radial displacements a basis of probability independent of the rotation measurements by Mr. Adams and Miss Lasby, which taken separately show consistent differences between certain lines and elements.

The determination of angular velocities from the rotation period of spots and flocculi furnishes additional data with which the results of the present investigation may be compared. The combined data are given in Table XVI. The values for the angular velocities in the cases of H_α, *Ca* 4227, *La*, and the reversing layer are based upon the data given by Mr. Adams in *Publications of the Carnegie Institution*, No. 138. The data for the H_δ flocculi and for the H_2 flocculi are from Mr. Hale's "Preliminary Note on the Rotation of the Sun as Determined from the Motions of the Hydrogen Flocculi."[1] The spot values are the means of the determinations by Carrington, Spörer, and Maunder, from the original papers. The values for the K_3 line of calcium are from my paper "On the General Circulation of the Calcium Vapor."[2]

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 25; *Astrophysical Journal*, **27**, 219, 1908.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 48; *Astrophysical Journal*, **32**, 36, 1910.

There are two methods of comparing the angular velocities determined from different objects and elements on the sun in order to determine the relative levels. The rate of change in angular velocity with latitude may be used as a criterion, and also the comparison of the absolute values of the observed velocities. In the case of spectrographic determinations in which the proper motions play a very subordinate part and in which repeated determinations reduce the accidental errors of observation and measurement to a minimum, the variation with latitude is without doubt the more reliable criterion; but when the objects under observation are

TABLE XVI

ANGULAR VELOCITY AND LEVEL

Latitude	St. John K_3	Adams H_α	Hale H_δ Floc.	Adams Ca 4227	Hale H_3 Floc.	Kenwood-Yerkes H_3 Floc.	Adams		Spot Means
							Rev. Layer	La	
0°.....	15°5	15°0	14°6	14°9	14°42	14°61	14°54	14°50	14°40
5.....	....	....	....	....	14.38	14.50	14.51	14.47	14.38
10.....	....	....	....	....	14.32	14.36	14.43	14.39	14.31
15.....	15.4	14.9	....	14.8	14.28	14.20	14.31	14.24	14.20
20.....	....	....	....	....	14.27	14.11	14.13	14.06	14.06
25.....	....	....	....	....	14.17	13.91	13.91	13.82	13.89
30.....	15.3	14.7	....	14.3	13.98	13.78	13.67	13.54	13.69
Means..	15.4	14.8	14.6	14.7	14.26	14.20	14.22	14.17	14.13
0°–30°.	0.2	0.3	....	0.6	0.44	0.83	0.87	0.96	0.71
Radial displacement.	−0.063	−0.050	−0.005	−0.002	−0.044		+0.025	+0.028	....

subject to large proper motions, as in the case of spots and flocculi, the relation between the angular velocity and the latitude cannot be determined with a high degree of precision. Mr. Maunder calls attention to the great range in the angular velocities given by the spots within a five-degree zone. The rotation periods within such a zone differ by more than twice the greatest difference between the means of the zones, and for latitudes greater than 25° there is slight indication of grouping of the rotation values about a mean. It is precisely the values dependent upon the extreme latitudes of the spot and flocculi regions that are of importance in

determining the law of variation with latitude. In zones where spots and flocculi are sufficiently numerous, the effect due to proper motion may in a measure be eliminated. In Table XVI both methods of considering the data are indicated. The mean angular velocities refer to no one latitude, but in the means the effects of accidental errors are lessened for latitudes where spots and faculae are less numerous. The numbers in the line $0^\circ - 30^\circ$ give the equatorial acceleration in passing from $\pm 30^\circ$ to the equator. The bottom line shows the radial displacements for the corresponding lines, and these furnish a third criterion of level. In regard to some of the lines and objects, the deductions from the data appear clear and well founded. The high levels of the K_3 line of calcium and the H_α line of hydrogen and their relative levels are shown by the concurrent evidence of all three criteria: high angular velocity, small equatorial acceleration, and large radial displacement. The high angular velocity for H_α, and the small equatorial acceleration have been confirmed by Perot.[1] The exact relative level of the H_δ line of hydrogen is uncertain, but all the evidence indicates a high level for its origin, but not so high as for the H_α line. In a preliminary investigation of the sun's rotation by the displacements of the hydrogen lines Mr. Adams[2] included the H_γ and H_δ lines. Of the results he says:

> There seems to be some tendency for H_α to give larger values than those furnished by the other two lines. Until additional material, however, is available, particularly for H_γ and H_δ, it is hardly justifiable to consider this difference in velocity real.

Mr. Hale[3] says of the results for the hydrogen flocculi taken with the H_δ line:

> The hydrogen flocculi, however, show no systematic variation of velocity with latitude. As already remarked, the hydrogen measures are less reliable than those of calcium, because of the inclusion of a less number of flocculi, larger proper motions, and more rapid changes of form. We may therefore take the mean value for ξ for all zones ($14^\circ.6$) as a provisional determination of the daily motion of the hydrogen flocculi.

[1] *Comptes rendus*, **151**, 430, 1910.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 24; *Astrophysical Journal*, **27**, 213, 1908.

[3] *Loc. cit.*

The H_δ flocculi upon which measurements were made were well distributed in latitude so that the weights for the high and low latitudes are quite comparable, and the absence of systematic change in angular velocity with latitude is an indication of high weight in assigning the level. The radial displacement of -0.005 Å, shown by the H_δ line, points also to a high level. This value, however, is affected by large accidental errors. The line is so nearly coincident with an iron line that the measures are difficult, particularly so in the case of radial displacements, as the two lines are displaced in opposite directions, and the absolute displacements differ on different plates so that the appearance of the line changes greatly. There is no doubt concerning the sign of the displacement. Its numerical value, however, is probably too small. The radial displacement of H_γ is -0.033 Å, but H_δ is the stronger of the two lines, and in the preliminary paper by Adams the measurements show a rotation value for H_δ between the values for H_α and H_γ, from which a large negative displacement would be expected. The high level of the source of the line λ 4227 of calcium is shown by Mr. Adams' rotation measures and by the radial displacement, but its level with reference to H_δ is uncertain.

It will be noticed that the value for the H_2 flocculi given by the Mount Wilson plates are considered by themselves, and a higher level assigned to them than that indicated by the Kenwood and Yerkes measures which were made upon the large flocculi or portions of flocculi that are the striking features of calcium spectroheliograms. The Mount Wilson measurements were made upon the minute flocculi which are more widely distributed in latitude and possibly at a higher level. In my investigations of the movements of calcium vapor over the solar surface it appeared that the vapor producing the bright K_2 components was rising over the general surface, but not over the large bright flocculi in the neighborhood of spots. It was suggested that the rise over the general surface might occur mainly over the granulations, in which case the minute flocculi, the granulations of the spectroheliograms, would be the tops of the rising columns and a phenomenon of higher level than the more quiescent masses forming the larger flocculi. The high level of the flocculi on the Mount Wilson plates is indi-

cated by the small change of angular velocity with latitude. This indication is of weight in this particular instance, because the points in the extreme latitudes were relatively numerous, and the equatorial acceleration differs so widely from that of the reversing layer that, allowing a wide margin of error, the indicated level would still be high. The comparison by means, which tends to decrease the effects due to accidental errors in the extreme latitudes, shows a higher average velocity and therefore also a higher level than for the reversing layer. The level indicated by the radial displacement, -0.044 Å, is higher than would be inferred from the numerical values of the angular velocities, but not higher than would be consistent with the small change with latitude. The measurements of the radial displacements of the bright reversal are difficult and uncertain. They refer to the middle or the center of gravity of the line. The settings were made upon the violet and red components and the wave-length of the center of the line was determined by the method suggested by Adams.[1] The great width of the K_2 line implies an effective layer of great thickness within which the velocity radial to the axis of the solar vortex would vary greatly. In the case of the Mount Wilson spectroheliograms the dispersion of the spectroheliograph and the width of the second slit were of an order to allow the light from the entire width of the line to reach the plate. The center of the line was obliterated by the K_3 absorption line, so that the effects due to the edges of the line which are produced at a greater depth are emphasized in the spectroheliograms. In the case of the Kenwood and Yerkes measurements by Mr. Fox upon large flocculi, the level indicated by the equatorial acceleration is slightly above and that indicated by the mean of the velocities slightly below the reversing layer, and the relatively quiescent state over the large faculae in the neighborhood of spots would suggest that the level is near the upper portion of the general reversing layer. It seems probable, therefore, that these large flocculi belong rather to the upper reversing layer than to the chromosphere.

The measurements made by Mr. Adams and Miss Lasby upon

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 6; *Astrophysical Journal*, **23**, 45, 1906.

the lanthanum line, when reduced by a least-squares solution, yield an empirical formula that may be compared with that obtained by them from the whole series.

$$\xi = 10\overset{\circ}{.}68 + 3\overset{\circ}{.}82 \cos^2\phi \text{, lanthanum}$$
$$\xi = 11.04 + 3.50 \cos^2\phi \text{, mean of whole series}$$

The measurements from which these formulae are derived were made upon identical plates, including 436 exposures, distributed through 80° of latitude. In view of the probable absence of differing systematic errors the following comparisons are striking.

TABLE XVII

Angular Velocities of Reversing Layer and Lanthanum

	Latitude							Radial Displacement
	0°	15°	30°	45°	60°	75°	90°	
Rev. layer....	14°54	14°31	13°67	12°79	11°92	11°27	11°04	+0.025Å
Lanthanum...	14.50	14.24	13.54	12.59	11.64	10.94	10.68	+0.028
Rev. layer—*La*........	+0.04	+0.07	+0.13	+0.20	+0.28	+0.33	+0.36	−0.003

The level of the origin of the lanthanum lines is shown, by its low rotation value, large equatorial acceleration, and large radial displacement, to be below the level of the reversing layer given by lines of solar intensity 2.

The level of the spots given by a comparison latitude by latitude is below the reversing layer, while that indicated by the equatorial acceleration is above, as Mr. Adams has shown. The latter criterion depends for its value upon the measurement of spots in high and low latitudes, where it is doubtful whether the results have been or can be within many years sufficiently numerous to eliminate the influences of great proper motions. In view of the small differences in angular velocities, the level of the spot umbrae appears to be not far below the reversing layer studied by Mr. Adams. As deeply into the sun as observations extend, the angular velocity decreases with depth, and for a great difference in level, marked differences between the angular velocity of spots and reversing

layer would be expected in view of the large mass of data relating to the latitude zones in which spots are numerous.

In Wilsing's theoretical discussion of the law of the sun's rotation[1] he concludes that owing to internal friction the variation of angular velocity with latitude diminishes as the center of the sun is approached, until a surface is reached the particles of which rotate with sensibly constant angular velocity about a common axis. Limiting the comparison to spectrographic determinations, in which the influence of proper motion is a minimum, we have the result shown in Table XVIII. The regular increase in the equatorial acceleration from the small value given by K_3 to the large value given by lanthanum, and the progressive change in radial displacement from −0.063 Å to +0.028 Å between the two levels, indicate, however, that the change in the angular velocity with latitude increases with depth between the upper limits of the chromosphere to a very low level in the reversing layer.

TABLE XVIII

EQUATORIAL ACCELERATION AND DEPTH

	Line				
	K_3	*Ha*	λ 4227	Rev. Layer	*La*
0°−30°	+0°.2	+0°.3	+0°.6	+0°.9	+1°.0
Radial displacement	−0.063	−0.050	−0.002	+0.025	+0.028

The probable arrangement, in order of depth, of the regions effective in producing the phenomena in question is indicated in Table XVI from left to right, in so far as it can be determined from the available observational data. In its general outlines it may be considered to represent our present knowledge of the actual conditions in the solar atmosphere. That we are dealing with different levels seems clear, but the determination of the relative levels in some cases is as yet uncertain.

5. *Magnetic field and level.*—From the point of view that the line displacements due to motion radial to the axis of a spot vortex are criteria for determining the levels at which the spot lines are

[1] *Astrophysical Journal*, **3**, 247, 1896.

produced, it is of interest to obtain the field strengths at the levels indicated by the lines for which the separations are known in spot spectra and in the laboratory. In "A Summary of the Results of a Study of the Mount Wilson Photographs of Sun-Spot Spectra,"[1] Mr. Adams gives a list of lines for which the separations in the spot spectra have been measured by Miss Burwell, Miss Wickham, and

TABLE XIX

LABORATORY AND SPOT SEPARATIONS

λ	Element	Intensity	Group	Character Spark	Spark		Spot	
					Δλ	Field	Δλ	Field
5112.996	*Cr*	0	..	....	0.947	20,000	0.146	3080
5781.400	*Cr*	0	..	Triplet	1.090	20,000	0.125	2300
5783.288	*Cr*	2	..	Triplet	1.099	20,000	0.136	2470
5784.080	*Cr*	3	..	Triplet	1.080	20,000	0.110	2040
5785.188	*Cr*	2	..	Triplet	1.048	20,000	0.137	2610
5903.555	*Ti*	00	..	Triplet	0.876	17,500	0.118	2360
5938.035	*Ti*	000	..	Sextuplet	0.840	17,500	0.102	2125
5941.985	*Ti*	00	..	Sextuplet	0.905	17,500	0.137	2440
6064.853	*Ti*	00	..	Triplet	1.159	17,500	0.160	2410
6137.915	*Fe*	7	*b*	Triplet	0.654	16,000	0.100	2450
6189.594	*Va*	0000	..	Triplet	0.719	20,000	0.117	3210
6200.527	*Fe*	6	*b*	Sextuplet ?	1.026	16,000	0.098	1530
6213.644	*Fe*	6	*b*	Sextuplet	1.200	16,000	0.136	1810
6219.494	*Fe*	6	*b*	Sextuplet ?	0.991	16,000	0.096	1550
6233.408	*Va*	000	..	Triplet	1.048	20,000	0.109	2080
6266.550	*Va*	000	..	Triplet	1.688	20,000	0.175	2075
6301.718	*Fe*	7	*d*	Sextuplet ?	1.063	16,000	0.119	1790
6303.985	*Ti*	000	..	Octuplet ?	0.565	17,500	0.093	2880
6312.456	*Ti*	00	..	Octuplet ?	0.766	17,500	0.091	2080
6331.067	*Fe*	2	*b*	Sextuplet ?	0.820	16,000	0.149	2930
6337.048	*Fe*	7	*d*	Sextuplet	1.293	16,000	0.151	1860
6344.371	*Fe*	4	*b*	Sextuplet ?	0.771	16,000	0.091	1890
6400.217	*Fe*	8	*d*	Sextuplet ?	0.802	16,000	0.086	1720
6411.865	*Fe*	7	*d*	Sextuplet ?	0.686	16,000	0.086	2000
6531.617	*Va*	000	..	Triplet	1.262	20,000	0.161	2550

himself. In using these for the present purpose only the lines that were measured as doublets in the spot spectra have been taken. These are given in Table XIX with the related data. The laboratory separations for iron and titanium are from Mr. King's paper;[2]

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 40; *Astrophysical Journal*, **30**, 124, 1909.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 56; *Astrophysical Journal*, **34**, 225, 1911.

for vanadium from Mr. Babcock's paper on the Zeeman effect for vanadium;[1] and for chromium Mr. Babcock has kindly supplied the data, partly from his as yet unpublished results. The plate numbers are T 102, T 105, and T 154, and the Greenwich spot numbers are 6393, 6441, 6511, and 6577.

The results for the separate elements arranged in order of line-intensity are given in Table XX.

TABLE XX

MAGNETIC FIELD AND LINE INTENSITY

Element	Intensity									
	oooo	ooo	oo	o	2	3	4	6	7	8
Va ..	3210 (1)	2310 (2)	2080 (1)	.....	.....	.....	.....	.....	.....	.....
Cr ..	.....	.....	.....	2690 (2)	2540 (2)	2040 (1)	.....	.....	.....	.....
Ti ..	.....	2500 (2)	2320 (4)	.....	.....	.....	.....	.....	.....	.....
Fe ..	.....	.....	.....	.....	*b* 2930 (1)	.....	*b* 1890 (1)	*b* 1630 (3)	*b* 2450 (1)	*d* 1720 (1)
Fe ..	.....	.....	.....	.....	.....	.....	.....	.....	*d* 1893 (3)	.....

TABLE XXI

MAGNETIC FIELD AND LEVEL AS INDICATED BY DISPLACEMENTS

Intensities ...... Elements	oooo–oo *Va, Ti*	o *Ti, Cr*	2–4 *Cr, Fe*	6–7 *Fe*	8–9 *Fe*
Field strength	3210 (1) 2310 (2) 2080 (1) 2500 (2)	2690 (2) 2320 (4)	2540 (2) 2040 (1) 2930 (1) 1890 (1)	1630 (3) 2450 (1)	1883 (3) 1720 (1) ....
Means	2485 (6)	2443 (6)	2388 (5)	1835 (4)	1842 (4)
Radial displacements	+0.034	+0.030	+0.023	+0.014	+0.006

With the exception of some irregularities in the case of iron, all four elements show decreasing field strength with increasing intensity of the lines. In forming the final means in Table XXI the values were weighted according to the number of lines of each intensity. The figures in parentheses give the number of lines.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 55; *Astrophysical Journal*, **34**, 209, 1911.

The intensities are grouped so that approximately equal weights may be assigned to each mean, and the titanium lines and the *d* lines of iron, which are at higher elevations than lines of like intensities of vanadium, chromium, and the lines of iron belonging to group *b*, are grouped with lines of the same approximate level.

As is seen by comparison with the chart (Fig. 1), the field strength near the lowest level of the reversing layer is 2485 gausses; and at the level of *Fe* lines of intensity 6–9, it is approximately 1838 gausses, which points to a low gradient along the axis of the vortex. The summary also shows a direct relation between field-strength and radial displacement.

6. *Anomalous dispersion.*—The bearing of the data obtained in this investigation upon anomalous dispersion in reference to solar phenomena is of interest, as radial displacements have been explained by Julius as a consequence of anomalous dispersion in the solar atmosphere.[1] In the figure given to illustrate the way anomalous dispersion acts in producing the shifts of the lines found in the Evershed effect, the red edges of the lines on the peripheral border of the penumbrae are broadened by a rapidly decreasing shading, while the violet border is sharp and the effect decreases from the inner edge of the penumbra outward. This does not represent the conditions found on the plates taken for this investigation, as upon these plates the lines appear to be shifted bodily and are equally sharp on the two edges, and the maximum displacement is at or near the outer border of the penumbra.

Three facts in particular, shown by the data given in this paper, require explanation from the point of view of anomalous dispersion: (1) the variation of displacement with wave-length, which is not a direct result of anomalous dispersion; (2) the systematic variation of displacement with the intensities of the lines; (3) the displacements of lines of the same element in opposite directions, as in the cases of *Ca*, *Na*, *Mg*, *Fe*, *Sr*, which seem to present great and apparently insuperable difficulties for the anomalous dispersion theory.

In a paper on the displacement of the spectrum lines at the sun's limb, Mr. Adams compared the laboratory results on anomalous dispersion with the displacements at the limb, and found no

[1] *Physikalische Zeitschrift*, **11**, 65, 1910.

clear relationship between the two phenomena.[1] In commenting upon this Julius says:

That a simple comparison of Geisler's observations on anomalous dispersion of metallic vapors in the arc with displacements at the limb—as given by Adams on page 28—could not possibly serve the purpose of finding such a relationship is evident. . . . . A peculiar feature of our explanation is that both very strong and very weak anomalous dispersion make the displacements small, whereas intermediate values give larger displacements.[2]

In view of the consideration that the basis of all astrophysical investigations rests upon the fundamental postulate that direct comparison is possible between the spectrum results obtained from terrestrial sources and the behavior of the spectrum lines in solar and stellar spectra, the first statement in the quotation is somewhat remarkable. It is difficult to devise a quantitative test of the theory of anomalous dispersion as applied to the sun; the above deduction from the theory, however, can be so used in comparison with laboratory results. It is postulated by the theory that weak and strong anomalous dispersion is associated with small solar displacements. Using as a basis Geisler's tables for anomalous dispersion, the comparison between lines common to his tables and to this paper shows the following:

TABLE XXII

DISPLACEMENTS AND ANOMALOUS DISPERSION

Lines Common to Both Lists	Anomalous Dispersion	Required by Theory	Observed
5 *Ca* lines, intensity 3–4	Very weak	Small	+0.019Å
2 *Mn* lines, intensity 3	?	Small	+0.028
3 *Cr* lines, intensity 2–3	Very weak	Small	+0.033
3 *Zn* lines, intensity 1–3	Very weak	Small	+0.032
2 *Ni* lines, intensity 3–4	?	Small	+0.030
1 *Sr* line, intensity 1	Very strong	Small	+0.030
2 *Al* lines, intensity 15–20	Moderate	Large	+0.001
2 *Fe* lines, intensity 15	Weak	Small	−0.005
2 *Na* lines, D_1 and D_2 20–30	Very Strong	Small	−0.006
2 *Mg* lines, intensity 20–30	{Weak / Very weak}	Small	−0.011
2 *Ca* lines, H and K	Strong	Small	−0.063
4 *Fe* lines, intensity 8–20	{Weak / Very weak}	Small	−0.003

Mean radial displacement for intensities 1 to 10=0.016 Å.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 43, 28; *Astrophysical Journal*, **31**, 57, 1910.

[2] *Astrophysical Journal*, **31**, 428, 1910.

In general, lines of weak intensity show small anomalous dispersion, and according to the above statement should give small displacements, but the measurements given in this paper show quite the reverse. The 16 lines of mean intensity 3 in the upper part of the table give a mean displacement of 0.027 Å, which is a large value, as may be seen from the mean (0.016 Å) of lines from intensities 1 to 10. There is one striking exception to the general rule that weak lines show small anomalous dispersion, and that is *Sr* λ 4607, which exhibits very strong anomalous dispersion, but gives, contrary to the theory, a very large displacement. The two aluminum lines show a moderate degree of anomalous dispersion, and, according to Julius, such lines should give large displacements in the sun; the value, however, is 0.001 Å. The two lines of iron of intensity 15 and the magnesium lines b_1 and b_2 show weak and very weak anomalous dispersion, the D_1 and D_2 lines of sodium and the H and K lines of calcium a larger amount. In these four cases the above deduction from the anomalous dispersion theory requires small positive solar displacements. The actual values are −0.005, −0.006, −0.011, and −0.063 Å, opposite in direction to the demands of the theory. The four lines of iron of intensity 8 to 20 show weak and very weak anomalous dispersion and small displacement, and are the four lines out of the thirty whose displacements are not opposed to the deduction from the theory; but they are moderately high-level lines and should show small radial displacements.

In the paper by Julius to which reference has been made he remarks:

> That the lines of the elements of very high atomic weight, such as lanthanum and cerium, show very small displacements [at the sun's limb] is easily accounted for if we assume their vapors to be extremely rare in the solar atmosphere. This explanation is certainly not less simple than the one proposed by Adams on pp. 17 and 18 of his paper, where he has to find a way out of the discrepancy to which in that case the pressure hypothesis appears to lead.

It is of interest in view of this explanation, from the point of view of anomalous dispersion, to note that the displacements of the lanthanum and cerium lines in the edges of the penumbrae of eccentrically located spots are very large, larger, in fact, than for

the lines of any other element except lead (at. wt. 207), ytterbium (at. wt. 173), and niobium (at. wt. 94), from which it is evident that vapors of the elements that occur in small quantities in the solar atmosphere give the largest radial displacements. If the displacements at the limb and in spot penumbrae are due to anomalous dispersion, it is somewhat difficult to reconcile the very small displacements of the lines of these elements in one case with the very large displacements of the same elements in the other. And if the effects due to anomalous dispersion are small in the case of lanthanum and cerium because of the rarity of these vapors in the solar atmosphere, the relatively great brightness of the weak solar lines of these elements in the flash spectra of Mitchell and Campbell seems difficult of explanation from the point of view of anomalous dispersion.

According to the dispersion theory there is no displacement or bending of the lines by refraction when the slit of the spectrograph is perpendicular to the radius of the solar disk passing through the center of the umbra. After speaking of the effect when the slit is parallel to the radius, Julius says:[1] "Bei jeder anderen Richtung des Spaltes muss der Effekt geringer sein; er verschwindet, wenn der Spalt den Fleck in einer Richtung senkrecht zu einer Verbindungslinie zwischen dem Fleck und dem Mittelpunkte halbiert." Displacements of the H and K line are observed, but much less frequently, with the slit perpendicular than with it parallel to the radius. The parallel position often shows displacements when, on exposures taken on the same plate and the same spot with the perpendicular position, no displacement is observable. Both displacements are very simply explained as Doppler effects, indicating an inflow into practically all spots and occasionally a cyclonic movement of the high-level vapor in the case of particularly strong and regular spots.

In the case of the winged lines, the anomalous dispersion theory considers that the core of the line is a pure absorption effect. Of H_β Professor Julius says:[2] "Die schmale mittlere Linie nun ist die wahre Absorptionslinie H_β, die natürlich durch Brechung nicht

[1] *Physikalische Zeitschrift*, **11**, 65, 1910.

[2] *Ibid.*, p. 66.

verschoben oder gekrümmt werden kann." The measurements upon the strong winged lines are of necessity made upon the central portion, the hard and sharp core. The plates taken in the course of this investigation for determining the displacements of the winged lines of *Fe*, *Na*, *Mg*, *Al*, *H*, and *Ca* were so strongly exposed and developed that the wings were obliterated and the measurements were made upon what the anomalous dispersion theory considers are true absorption lines, so that the displacements in the case of these lines would seem to be free from effects due to that cause.

The relative displacements of the lines of the reversing layer at the east limb and west limb of the sun have never been attributed to anomalous dispersion. The agreement between the levels shown by rotation results and radial displacements would tend to show that the radial displacements are independent of anomalous dispersion, and represent probably a Doppler effect.

The effects due to anomalous dispersion in certain laboratory experiments are so striking that, from the point of view of the physicist, it has seemed improbable that they would be generally absent from solar phenomena. The absence of displacements of solar lines that may with certainty be ascribed to anomalous dispersion has been attributed generally to the small quantity of vapor of any one element in the solar atmosphere. But as has been shown for calcium, the quantity above the level of lines of intensity unity is probably equivalent to a column some sixty-seven meters long at 3000° C., and under a pressure of one atmosphere. This is a far greater quantity than is necessary to produce the marked anomalous dispersion shown by the H and K lines in laboratory experiments. In a paper "On the Application of the Laws of Refraction in Interpreting Solar Phenomena,"[1] Mr. Anderson compares the conditions in the sun with the conditions under which anomalous dispersion is obtained in the laboratory. The photosphere subtends over the general disk practically an angle of 180° at any point in the solar atmosphere—reversing layer or chromosphere—and may be considered an infinite, plane, self-luminous surface. Such a surface, he shows, would appear uniformly lumi-

[1] *Astrophysical Journal*, **31**, 166, 1910.

nous even if covered by an atmosphere full of *Schlieren*, provided the deviation does not exceed 90°. He shows further that in the case of solar phenomena the angles of deviation are small, and that the absorption bands would have exactly the same width and character as they would have if produced by a perfectly homogeneous atmosphere of the same absorptive power. It seems probable that observable effects due to anomalous dispersion in the solar atmosphere are exceptional, and that until we are able to depend upon measurements of solar wave-lengths to the fourth decimal place, at least, its contribution to the relative positions of the Fraunhofer lines, if any, will be masked by phenomena due to other causes.

7. *Solar and terrestrial analogies.*—The percentage composition of the terrestrial atmosphere does not change appreciably within 15 km above the earth's surface, owing to the mixing process kept up by storms and convection currents. Above that level the density of the heavier gases decreases more rapidly than that of the lighter gases, so that with increasing elevation the lighter gases gain in percentage, though decreasing in absolute density, until at 100 km hydrogen forms 99.5 per cent and helium 0.5 per cent of the atmosphere.[1] The march of conditions in the regions of the solar atmosphere accessible to observation appears to be very like that in the terrestrial atmosphere, the lighter constituents gaining in percentage over the heavier ones at higher levels. The slope of an imaginary line drawn through the highest levels given in the chart (Fig. 1) is probably too great, because of the lack of strong lines given by the heavier elements; but if we should grant to all elements lines of equal intensity in the solar spectrum, it would still follow that the heavier elements are at the lower levels. For if we place at the extreme right the element whose lines actually present in the solar spectrum originate the farthest below iron lines of the same intensity, and precede it by the elements whose lines determined by reference to the same iron scale originate at successively higher levels, the last eight in the series will be: *Nd* 144, *Ba* 137, *La* 138, *Pb* 207, *Cd* 112, *Yb* 173, *Nb* 94, *Ce* 142. These are the eight heaviest elements in the list, having an average atomic

[1] Hann, *Lehrbuch der Meteorologie*, p. 8, 1906.

weight of 143 against an average of 49 for the other 19 elements considered.

In the terrestrial atmosphere below 3 km there is a turbulent stratum, the region of storms and powerful convection currents and irregular temperature gradients. Above this stratum and below 10 km is the region of comparatively uniform changes where the normal condition is one of stability, though during storms it may be the seat of vertical convection currents. Lastly is the outer relatively quiescent stratum, the region of a uniform or inverted temperature gradient, intermingling but slightly with the underlying levels. The division between the two lower layers is less pronounced than that between them considered as one region and the outer layer.[1]

In the lower solar atmosphere, the region including the lowest levels of the reversing layer, and especially the underlying gases, is the region of tremendous disturbances in which the upper portion of the sun-spot vortex is located, in which occurs the outflow of material from the interior of the sun, and where more or less mixing must occur. Above this turbulent region, yet more or less involved in its activities, is the general reversing layer, whose normal condition seems to be one approaching more nearly a stable state. The chromosphere seems quite sharply distinguished from this region both in its composition and in the movements of its constituent gases near spots. The separation appears to be at the level of zero tangential velocity, or the level of velocity-inversion in the case of the flow radial to the axis of the solar vortex. In the case of terrestrial cyclonic storms, but little is known from direct observation of the atmospheric movements over the center of the storm, while, in the case of storms in the solar atmosphere, the point of observation is from the outside and the upper movements are those directly detected. It would be interesting if our knowledge of terrestrial cyclonic storms should be supplemented by solar observations.

Though the general circulation of the two atmospheres may have little in common, it seems quite probable that cyclonic storms, whatever their determining causes, will follow the same hydro-

[1] Moore, *Descriptive Meteorology*, p. 119, 1910.

dynamical laws, and that observations in regions so widely separated as the sun and earth may be combined in studying the complete cyclonic system.

There is nothing in the deductions from the observations that suggests a stratification of the solar atmosphere. If, for the present, we leave helium and the coronal material aside, and confine the considerations to the elements included in this investigation, the indicated distribution is easily imagined. As one penetrates this atmosphere from without the sun, he would first encounter an atmosphere due to "that form of calcium vapor that produces the H and K lines"; to this is successively added hydrogen and the vapors of magnesium, sodium, iron, aluminum, etc., each increasing in absolute density with the depth until in the lowest portion of the reversing layer occur also the vapors of all the elements whose lines appear in the solar spectrum.

GENERAL CONCLUSIONS

1. The differing displacements shown by the Fraunhofer lines at the peripheral edges of the penumbrae of eccentrically located sun-spots seem to find their simplest explanation in movements of the solar vapors tangential to the solar surface with velocities varying with the elevation.

2. Assuming as a standard the series of displacements shown by the *Fe* lines, which decrease regularly from +0.034 Å for intensity 00 to +0.004 Å for intensity 10, the relative levels of the lines of 26 other elements of the reversing layer and chromosphere have been determined and plotted in a chart of distribution.

3. The resulting distribution shows that the H_3 and K_3 lines of calcium are the lines of highest level, followed by the H_α line of hydrogen, and that, in the main the heavy and rare elements occur in detectible amounts only in the lower portions of the solar atmosphere.

4. The enhanced lines show smaller radial displacements than unenhanced lines of the same solar intensities and would appear to originate at higher levels in and near sun-spots.

5. The *Fe* lines of groups *d*, *sub-d*, and *e* show smaller displacements than those of group *b* and are assigned a higher level.

6. The quantities of absorbing vapors in the solar atmosphere seem sufficient to produce in general complete absorption.

7. Large positive radial displacements are associated with low heights above the photosphere and large negative displacements with great heights, when a comparison is made between radial displacements and elevation deduced from eclipse results.

8. The mean radial displacement of lines of the reversing layer occurring frequently in flash spectra is +0.009 Å; of those observed less frequently it is +0.023 Å.

9. A comparison of the radial displacements with the weakening and strengthening of spot lines shows that strengthening increases with depth, and that weakening is associated with high elevations.

10. A discussion of the displacements between the center and limb of the sun from the point of view of levels as indicated by radial displacements leads to the conclusion that pressure plays the predominating rôle in the phenomenon, but that the effect is modified by the scattering of light in the lowest levels and by the downward movement of the high-level vapors.

11. When the Mount Wilson rotation results are compared in detail with the corresponding radial displacements, a remarkable agreement is found. Low values for solar rotation are associated with large positive radial displacements, and high values for rotation with large negative radial displacements. The data in both cases place the level of the lanthanum lines below, and the level of the hydrogen lines above, the mean level of the reversing layer.

12. When the strength of the magnetic field in sun-spots is calculated from the separations in spot spectra and the laboratory separations of the same lines in known magnetic fields, widely different values are obtained, but when the lines are assigned to the relative levels indicated by their radial displacements the field strength decreases consistently with elevation.

13. According to the theory of anomalous dispersion, both very weak and very strong anomalous dispersion makes the displacements of the Fraunhofer lines small, whereas intermediate values give larger displacements; and in the case of the winged lines the core is the true absorption line and is not displaced by refraction.

Judged by these criteria radial displacements in the penumbrae of sun-spots are not due to anomalous dispersion as none of the above criteria is satisfied.

14. The displacements of the Fraunhofer lines in the penumbrae of sun-spots give a means of sounding the solar atmosphere and of assigning relative levels to the sources of the lines. Aside from the inherent probability of the interpretation, it is confirmed by eclipse results and is in harmony with a wide range of solar observations, and opens the way to further solar research.

Mount Wilson Solar Observatory
May 31, 1913

THE NON-SELECTIVE TRANSMISSIBILITY OF RADIATION THROUGH DRY AND MOIST AIR

By F. E. FOWLE[1]

Determinations of the non-selective absorption of radiation between the wave-lengths $0.34\,\mu$ and $1.7\,\mu$ associated with atmospheric aqueous vapor and of the general transmission coefficients for radiation passing through a dry atmosphere are here given. The observations used were made during two years when the atmosphere was of exceptional purity relative to foreign particles, such, for instance, as volcanic dust.

METHOD AND DATA

Briefly, the procedure consists in correlating the atmospheric scattering of solar radiation with the amount of water-vapor present. In an earlier paper[2] were given the determinations of the amount of aqueous vapor above Mount Wilson, stated as so much precipitable water, for some 180 days of the years 1910 and 1911. This amount of water-vapor was found by means of the depths of certain bands produced by it in the infra-red spectrum, under standard spectroscopic conditions, as discussed in a yet earlier communication.[3] On most of these days, the transmissibility of radiation through the air above Mount Wilson was available from the regular determinations of the solar constant of radiation. It was computed at 23 wave-lengths in 1910, 33 in 1911, within the above-mentioned wave-length interval.

The transmissibility at any wave-length varies from day to day, depending, it may be supposed, on the amount both of dust and of aqueous vapor present. The days of observation were divided into groups according to the amount of aqueous vapor present. At each wave-length a mean coefficient of transmissibility for each group was obtained. This for a given wave-length may be considered as made of two parts, one $a_{w\lambda}$ depending upon the water-vapor and

[1] Published by permission of the Secretary of the Smithsonian Institution.

[2] *Astrophysical Journal*, **37**, 359, 1913. [3] *Ibid.*, **35**, 149, 1912.

variable from group to group; the other, $a_{a\lambda}$ which, were the observations numerous enough, might be considered as constant and due to dry air of average transparency. It is here assumed that the dates included in each group were distributed sufficiently at random.

The units were so chosen that $a_{a\lambda}$ is the mean vertical atmospheric transmissibility above Mount Wilson of radiation through dry air at the wave-length λ, and $a_{w\lambda}$ the corresponding factor of change of transmissibility when there is 1 cm of "precipitable" water in the form of vapor distributed in a vertical column of the atmosphere. Then if w is the depth in centimeters of the precipitable water in the atmosphere and a_λ the corresponding transmissibility,

$$a_\lambda = \mathring{a}_{a\lambda} a_{w\lambda}^{w}$$

or, taking logarithms,

$$\log a_\lambda = \log a_{a\lambda} + w \log a_{w\lambda} \ .$$

Hence if the observations are plotted with the two quantities derived from the observations as co-ordinates, that is, with log a_λ as ordinates and w as abscissae and the best representative right line drawn, the tangent of its inclination to the axis of abscissae will be log $a_{w\lambda}$, the logarithm of the coefficient of transmissibility of radiation, associated with atmospheric water-vapor (1 cm precipitable water) and the intercept on the axis of ordinates will be log $a_{a\lambda}$, the logarithm of the coefficient of transmissibility through dry air.

In Fig. 1 are shown the plots of the group-means for five different wave-lengths and the representative right lines used. Each group into which the data were collected is represented by a point and, except that for the greatest amount of vapor, depends on the observations for ten dates. Each line depends upon some 180 observations except those for the ten wave-lengths for which 1911 data alone were available. In Table I is given a sample set of data. The divergencies of the various points from the representative lines are an indication that the ten observations do not give chance the opportunity to produce a sufficiently representative mean, rather than that there is not a very definite correlation between aqueous vapor and the coefficients of transmissibility. Both abscissae and

ordinates of the data of the wettest days have less weight. It was thought best to plot and reduce each year separately. The results were then weighted according to their grades so that 1911 usually

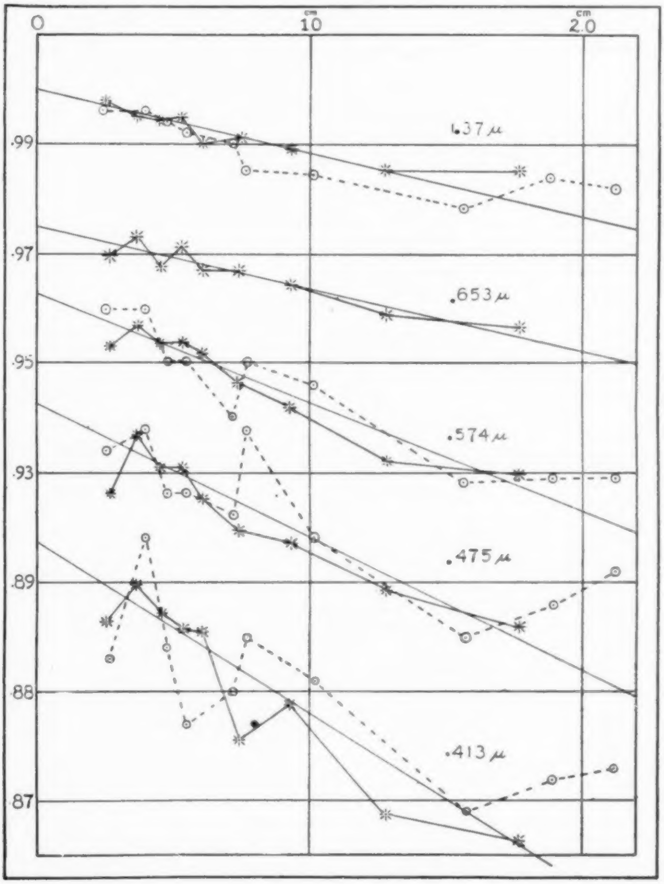


FIG. 1.—Transmissibility of radiation through moist air above Mount Wilson. Ordinates are logarithms of transmissibilities. Abscissae are centimeters of precipitable water in vertical column of atmosphere.

had double weight because improved reduction methods rendered its transmissibility coefficients for radiation through air more reliable. The resulting coefficients for water-vapor throughout the

spectrum agree for the two years within three- or four-tenths of 1 per cent. The resulting values for $a_{w\lambda}$ and $a_{a\lambda}$ are shown in Fig. 2.

TABLE I

Atmospheric Transmissibility Coefficients at 0.384 μ as Dependent upon Aqueous Vapor, 1911

Precipitable Water

Means	cm 0.268	cm 0.364	cm 0.454	cm 0.535	cm 0.603	cm 0.746	cm 0.929	cm 1.279	cm 1.768
	0.667	0.692	0.708	0.676	0.650	0.711	0.718	0.*664*	.....
	.745	.690	.686	.703	.697	.698	.702	.*665*	.....
	.684	.715	.687	.652	.718	.615	.673	.655	.....
	.708	.695	.723	.718	.724	.670	.655	.596	.....
	.681	.686	.705	.682	.698	.686	.673	.692	.....
	.692	.692	.679	.718	.714	.678	.686	.695	0.*700*
	.706	.719	.681	.665	.687	.706	.664	.697	.*700*
	.702	.656	.711	.681	.700	.706	.666	.*700*	.604
	.698	.714	.708	.711	.653	.692	.*664*	.*700*	.*662*
	0.686	0.682	0.695	0.697	0.653	0.698	0.*665*	0.*662*	0.650
Means..	0.6976	0.6941	0.6983	0.6903	0.6894	0.6860	0.6766	0.6726	0.6632

The values in italics were used in two groups.

TRANSMISSIBILITY OF RADIATION THROUGH DRY AIR

The upper curve *a* of Fig. 2 represents the transmissibility of radiation through the dry air vertically above Mount Wilson (altitude 1730 m), at a period when the air was exceptionally free from volcanic matter. The transmission ranges from 0.684 at the wave-length 0.3709 μ to 0.992 at 1.73 μ. The values for wave-lengths shorter than 0.3709 μ are of doubtful worth, the increased transmissibility being very probably an effect of the field light in the spectroscope. There is a depression in the curve from about wave-length 0.5026 μ to 0.7644 μ probably due to selective absorption in the permanent gases of the earth's atmosphere. A table is inserted in the plot indicating at the proper places all the atmospheric lines included in Rowland's "A Preliminary Table of Solar-Spectrum Wave-Lengths,"[1] which extends from 0.297 μ to 0.733 μ. Rowland gives more than 440 atmospheric lines in this region between 0.5026 μ and 0.7644 μ besides those due to water-vapor.

[1] *Astrophysical Journal*, 1895–1897.

The dotted line above this region will be explained later. It is supposed to represent the transmissibility in this spectral region were it entirely non-selective (molecularly scattered?).

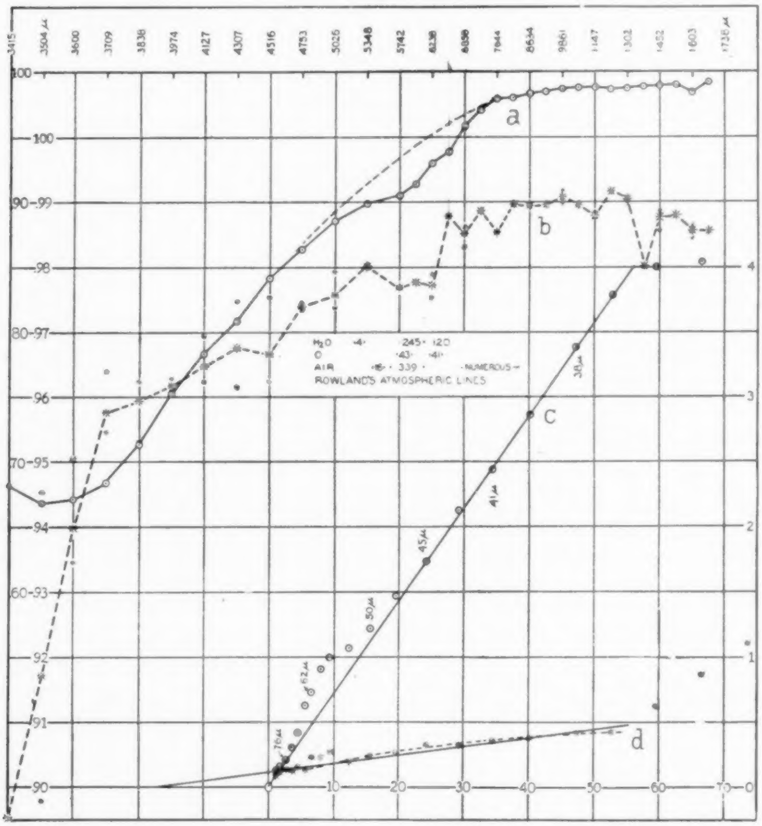


FIG. 2.—Curve a) Transmissibility of radiation through dry air vertically above Mount Wilson, 1910–1911. ($a_{a\lambda}$)

b) Factor of change produced by atmospheric aqueous vapor (1 cm precipitable water). ($a_{w\lambda}$)
Ordinates for a and b: transmissibilities;
Abscissae for a and b: deviations ultra-violet glass prism.
The corresponding wave-lengths are inserted at the top.

c) Ordinates, values of C, where $a_{a\lambda}=e^{-C}$ (dry air);
Abscissae, $\lambda^{-4}\times 10^{-16}$.

d) Ordinates, values of C, where $a_{w\lambda}=e^{-C}$ (water vapor);
Abscissae, $\lambda^{-4}\times 10^{-16}$.

In the region of wave-lengths shorter than 0.5 μ Rowland does not give a single atmospheric line. There may be a few. Cornu,[1] observing with a quartz spectroscope set at 0.423 μ, examined the spectrum of the electric lights on Eiffel Tower 4350 m away (=0.54 atmosphere) and observed no telluric lines at this end of the spectrum even though the evening was rainy. His observations were limited at 0.329 μ by the glass lens over the tower light. He gives as the tension of the water-vapor in the air 8.6 mm, which corresponds to about 4 cm precipitable water in the path of his beam.

The great oxygen bands at A and B were eliminated in the present study by drawing a smooth curve over their tops in the bolographs and making on that curve the measures in the corresponding parts of the spectrum in order to measure only the non-selective absorption.

TRANSMISSIBILITY OF RADIATION THROUGH ATMOSPHERIC WATER-VAPOR

The dotted curve b of Fig. 2 gives the factor of change in the transmissibility of radiation through air when it contains 1 cm precipitable water in the form of vapor as it actually exists in a vertical column through the atmosphere. It ranges from 0.957 at the wave-length 0.37 μ to 0.99 in the infra-red. The depression between 0.535 μ and 0.650 μ is due to the selective absorption of some fine aqueous vapor lines. Because of the non-homogeneity of the radiation the transmission coefficients are doubtless somewhat too great in this region. The great water-vapor bands a, α, ρ, Φ, Ψ, and Ω and the oxygen bands at A and B were eliminated by using smoothed bolographs as in the case with dry air.

MOLECULAR SCATTERING OF RADIATION IN AIR

Rayleigh and Schuster have shown that if E_0 is the incident energy, E the energy transmitted through a gas, x the length of path, e the base of the natural logarithms, μ the index of refraction, λ the wave-length, and N the number of molecules per unit of volume, then

$$E=E_0e^{-kx}$$

where

$$k=\frac{32\pi^3(\mu-1)^2}{3N\lambda^4}\ .$$

[1] *Astrophysical Journal*, **13**, 142, 1901.

L. V. King has quite recently further elaborated this analysis and used it[1] in the discussion of the Smithsonian measures.[2] He derives the following expression:

$$C_x=\frac{32}{3}\left\{\pi^3(n_0-1)^2\frac{H}{N_0}\lambda^{-4}+a_0H\right\}\frac{p}{p_0}+\text{(term due to dust)},$$

where C_x corresponds to the k of the previous equation taken at the altitude x where the atmospheric pressure is p, p_0 the corresponding pressure at sea-level, H the height of a homogeneous atmosphere at 760 mm, 0° C., N_0 the number of molecules in a cubic centimeter at the same standard pressure and atmosphere, a_0H a term depending on the amount of energy absorbed and converted into heat. This equation is of the form $y=mx^{-4}+b$.

Through the relation $a_{a\lambda}=e^{-C_x}$, the coefficients of the earlier part of this communication were properly transformed and the results plotted in the lower right-hand part of Fig. 2. The steeper plot, c (circles), relates to air, the other, d (crosses), to water-vapor. The values of C_x were used as ordinates, $\lambda^{-4}\times 10^{-16}$, as abscissae. It seemed apparent that the right line best representing the points should pass through the zero of co-ordinates, making the last two terms of the equation for C_x zero. The points between the wave-lengths 0.503 μ and 0.764 μ lie in a region where strong selective absorption exists and therefore should not be taken into account. The value of the tangent m for this line was measured as 0.724×10^{-18}, whence

$$N_0=\frac{32}{3}\pi^3(n_0-1)^2\frac{Hp}{mp_0}$$

$$=(10.7)(31.0)(8.58\times 10^{-8})\frac{7.99\times 10^5 620}{.724\times 10^{-18}760}$$

$$=2.56\times 10^{19}$$

[1] *Philosophical Transactions of the Royal Society of London*, A **212**, 375, 1913. Schuster earlier discussed the matter and concluded that molecular scattering practically wholly accounts for the light scattered, although the data then available were far less adapted to the discussion than that of the present research (*Nature*, **81**, 97, 1909). Mention should also be made of the treatment of the matter on the electron theory by Natanson ("On the Theory of Extinction in Gaseous Bodies," Cracovie Académie des sciences, *Bulletin internationale math. et phys.*, p. 915, 1909).

[2] Abbot, Fowle, and Aldrich, *Annals of the Astrophysical Observatory of the Smithsonian Institution*, Vols. **2** and **3**.

which corresponds very closely to the value 27.1 billion-billion, probably the best value at present from other methods for the determination of the number of molecules per cc at 760 mm, 0° C. (Millikan). This indicates that over a considerable portion of the spectrum the depletion of energy from the direct beam from the sun or other celestial body is due to molecular scattering. Also that during these two years, 1910 and 1911, the average transparency of the sky above Mount Wilson was little affected by dust. What little dust there may have been would have tended to make the above value for N_0 too small.

A significant point is that this correspondence between theory and observation is a confirmation of the correct estimation of the atmospheric losses in the Smithsonian determinations of the solar constant of radiation.[1] This confirmation does not hold, however, in the region of selective absorption between 0.503 μ and 0.764 μ. Here the spectrum probably consists of regions of normal molecular scattering separated by narrow lines of selective absorption. Theoretically the observed transmission coefficients must be somewhat too great in this region. Certainly the molecular scattering even here predominates, because not only are most of the atmospheric lines very faint, especially above Mount Wilson, but the extent of spectrum they cover is small, as may be judged by their fewness compared to the number of solar lines in the same region. There were noted at sea-level by Rowland 3500 solar lines and 440 atmospheric lines. The intervening spaces between the lines count on the side of molecular scattering. Across the top of this selective-absorption band has been drawn in the upper curve *a* of Fig. 2 a dotted line computed from the corresponding points of the right line of the lower *air* plot and this represents the theoretical values for this region on the assumption of non-selective scattering.

THE SCATTERING ASSOCIATED WITH ATMOSPHERIC WATER-VAPOR

It is of interest to apply the same method of analysis in the estimation of the number of molecules corresponding to the depletion of radiation connected with atmospheric water-vapor. If N_w

[1] *Annals of the Astrophysical Observatory of the Smithsonian Institution*, Vols. 2 and 3.

be the molecules in a cubic centimeter at the temperature t and the pressure p, the density of aqueous vapor approximately[1]

$$\frac{0.81p\times10^{-3}}{(1+\alpha t)760}$$

which equals the weight in grams per cc, in other words the reciprocal of the height of a column 1 cm square, containing 1 cm precipitable water at the temperature t and the pressure p, then, taking 0.67×10^{-19} as the tangent of the representative line for the water-vapor data in the lower part of Fig. 2,

$$N_{tp}=\frac{32\pi^3}{3}\left\{\frac{(.000261)p}{(1+\alpha t)760}\right\}^2\left\{\frac{(1+\alpha t)760\times10^3}{(0.81)p}\right\}\frac{1}{0.67\times10^{-19}}$$
$$=(4.17)(10^{17})\left\{\frac{p}{(1+\alpha t)760}\right\}.$$

But assuming that Avogadro's law applies in this case of water-vapor, the number of molecules which would be expected is

$$N_{tp}=(2.7)(10^{19})\left\{\frac{p}{(1+\alpha t)760}\right\}$$

or about 64 times as many. Thus it is found that the scattering of radiation indicated by the water-vapor data is far greater than would be expected from the number of molecules of water-vapor present.

THE TRANSMISSIBILITY BY LIQUID WATER

Before discussing further the water-vapor results, it will be interesting to consider Table II, which contains some values of C determined by Kreusler[2] for a layer of liquid water 1 cm thick and extending over a considerable range of wave-lengths in the ultra-violet.

The data were plotted with C as ordinates and λ^{-4} as abscissae, and with the exception of the first three measures they lie remarkably well on a right line passing through the zero of co-ordinates. The first three values show greatly increased absorption as they approach a band of great selective absorption at $0.115\,\mu$ (metallic

[1] Jamin, *Annales de chimie et de physique* (3), **62**, 171, 1858, whence is taken also the index of refraction for water-vapor.

[2] *Annalen der Physik*, **6**, 412, 1901.

absorption[1]). In the last line of Table II are given the tangents of the line drawn from each separate point to the origin. The mean value is 1.15×10^{-21}, the tangent of the best representative right line for all the points.

TABLE II

TRANSMISSIBILITY BY LIQUID WATER

λ in μ	0.186	0.193	0.200	0.210	0.220
$\lambda^{-4} \times 10^{-16}$	833.	725.	625.	515.	427.
C	0.0688	0.0165	0.0090	0.0061	0.0057
$m \times 10^{+23}$	....	....	....	118.	134.
λ in μ	0.230	0.240	0.260	0.300	....
$\lambda^{-4} \times 10^{-16}$	357.	301.	219.	123.	....
C	0.0034	0.0032	0.0025	0.0015	....
$m \times 10^{+23}$	95.	106.	114.	122.	....

At yet longer wave-lengths the data determined by Ewan[2] and Aschkinass[3] are available and are given in Table III.

TABLE III

TRANSMISSIBILITY BY LIQUID WATER

λ in μ	0.415	0.430	0.450	0.475	0.487	0.500
$\lambda^{-4} \times 10^{-16}$	33.8	29.2	24.4	19.6	17.8	16.0
C Ewan	0.00035	0.00023	....	....	0.00014	....
C Aschkinass	....	....	0.00020	0.00020	....	0.00020
$m \times 10^{+23}$	104.	79.	82.	102.	79.	125.
C Fowle	0.035	0.032	0.32	0.026	0.025	0.024

The last line gives values for atmospheric water-vapor.

Beyond $0.50\,\mu$ another band of selective absorption is rapidly entered. The mean of the tangents for this set is 0.95×10^{-21}, so that these points lie very close to the line representing the first group.

Now suppose this centimeter-thick layer of liquid water were to have this same transmissibility in vapor form (corresponding to 1 cm precipitable water). Then in place of the tangent 0.67×10^{-19} either 1.15×10^{-21} or 0.95×10^{-21} would be substituted. The values for N_0 would be respectively 2.43×10^{19} and 2.94×10^{19}. The first value is surely too small for the data because the square of

[1] Martens, *Annalen der Physik*, **6**, 603, 1901.

[2] *Proceedings of the Royal Society*, **57**, 117, 1894.

[3] *Annalen der Physik und Chemie*, **55**, 401, 1895.

the index of refraction for water-vapor used applies to wave-lengths near the D lines. If the index varies as much with the wave-length for aqueous vapor as it does for air, then 2.43 should be increased by about 1/9 and becomes 2.70.

This would seem to lead to the conclusion that over this quite great range of wave-lengths, 0.210 μ to 0.500 μ (nearly an octave and a half), between the two bands of selective absorption centering at 0.115 μ and 0.600 μ, the depletion of light in passing through liquid water is due to molecular scattering, and that the molecules of liquid water behave like H_2O in scattering light, not as $(H_2O)_2$, dihydrol, or $(H_2O)_3$, trihydrol. Other properties[1] of water have led to the conclusion that liquid water is a mixture of $(H_2O)_2$ and $(H_2O)_3$, and that ice is $(H_2O)_3$.

ATMOSPHERIC AQUEOUS VAPOR

It is evident then that the radiation losses in passing through atmospheric aqueous vapor are not only much greater than could be accounted for by purely molecular scattering but are also very much greater than would occur in the transmission of rays of wave-lengths between 0.21 μ and 0.50 μ through the same quantity of water in the liquid state. This latter fact was unexpected, since at longer wave-lengths liquid water is far less transparent than the equivalent vapor. One cm of liquid water is practically opaque to radiation from 1.2 μ to 8 μ,[2] while as atmospheric vapor, except in the bands of great selective absorption, it transmits 99 per cent in this spectrum region.

Referring again to *d*, Fig. 2, probably the dotted line drawn more truly fits the data. This indicates a departure from strict proportionality between scattering and λ^{-4}. The departures are in the sense of giving relatively too high observed coefficients ($a_{w\lambda}$) in the violet and absolutely too high ones all through the spectrum as compared with what would be produced by the scattering by water-vapor molecules alone. Such an effect as this departure would result from encounters of the radiation with scattering obstacles of

[1] Röntgen, *Annalen der Physic und Chemie*, **45**, 45, 1892; Sutherland, *Philosophical Magazine* (5), **50**, 460, 1900.

[2] E. F. Nichols, *Physical Review*, **1**, 1, 1893; Coblentz, *Bulletin Bureau of Standards*, **7**, 632, 1911.

a greater order of magnitude than molecules, such for instance as hydrols, nuclei, ions, or dust.[1]

The evidence furnished by liquid water is perhaps against the supposition of hydrols. In deriving the transmissibility coefficients, $a_{w\lambda}$, the assumption was made that there was no correlation between dust and water-vapor. It may be that the dust content of the atmosphere is more or less proportional to the amount of water-vapor, although this seems somewhat improbable. Considerable evidence collected by Aitken[2] in the Alps and elsewhere seems to show no such proportionality. He even states that the greatest amount of dust may be present in the dryest weather.[3]

There remain the nuclei or the ions as a possible explanation of the abnormally great general absorption associated with atmospheric water-vapor. Ions are always present in the air, and if any water-vapor is present it will probably be condensed upon them in small drops which may be of the order of 10^{-7} cm. For a further discussion of ions as centers for the formation of small water particles the reader may be referred to chap. vii of the second edition of J. J. Thomson's *Conductivity of Electricity through Gases.*

Wilson[4] has shown that, under the influence of ultra-violet light, in moist dust-free air nuclei are formed and may grow "till they become large enough to scatter ordinary light." By careful laboratory researches he has shown that oxygen and water-vapor alone are necessary for their production; that water-vapor is necessary; that saturated vapor is not necessary; that they persist for some time after formation; that these nuclei are different from ions since they carry no electric charge; that they are probably due to some combination, H_2O_2, which by decreasing the vapor pressure allows drops of water containing one of them to form and to grow where pure water drops would evaporate. Bieber[5] has since shown that

[1] For instance, compare the effect of volcanic dust in 1912 when Mr. Abbot's observations in Bassour showed transmission coefficients due to the volcanic dust not varying by 1 per cent throughout the visible spectrum ($0.36\,\mu$ to $0.80\,\mu$), Abbot and Fowle, "Volcanoes and Climate," *Smithsonian Misc. Collections*, **60**, No. 29, 1913.

[2] *Transactions Royal Society of Edinburgh*, **37**, 17.

[3] *Ibid.*, **35**, 1.

[4] *Philosophical Transactions of the Royal Society*, **192**, 403, 1899.

[5] *Annalen der Physik*, **39**, 1313, 1912.

H_2O_2 is formed by the action of ultra-violet light. Although the ultra-violet energy in sunlight is too weak at the surface of the earth to be very efficient in the formation of these nuclei, in the clear air above Mount Wilson it may well be very active. In such nuclei, dependent directly upon the presence of water-vapor, there seems a sufficient explanation of the increased absorption.

Before concluding, the writer wishes to express his gratitude to Mr. Abbot for his criticisms and suggestions in the course of the preparation of this matter for publication.

SUMMARY

The change in the transmissibility of radiation associated with atmospheric water-vapor between the wave-lengths 0.371 μ and 1.74 μ has been determined. Thence became possible the evaluation of the transmissibility for dry air vertically above Mount Wilson (1730 m). In the following table are given for a few selected wave-lengths the coefficient of transmissibility for dry air, $a_{a\lambda}$, the factor for the change produced by atmospheric vapor when the amount of precipitable water is 1 cm, $a_{w\lambda}$, and the theoretical values for dry air computed from the theory of molecular scattering.

TABLE IV

	Wave-Lengths								
	μ 0.370	μ 0.400	μ 0.430	μ 0.460	μ 0.500	μ 0.600	μ 0.750	μ 1.00	μ 1.50
$a_{w\lambda}$	0.957	0.962	0.967	0.971	0.976	0.977*	0.988	0.990	0.988
$a_{a\lambda}$ (observed)	0.683	0.757	0.808	0.851	0.885*	0.916*	0.977	0.987	0.990
$a_{a\lambda}$ (computed)	0.680	0.755	0.808	0.850	0.890*	0.946*	0.977	0.987	0.986

* Places of selective transmission.

The corresponding values of a_λ for air containing w cm of precipitable water-vapor would be $a_{w\lambda}^{w} \cdot a_{a\lambda}$.

The transmission coefficient for dry air has been used for the determination of the number of molecules, N_0, per cc of a gas at 760 mm pressure and at 0° C. The result was

$$N_0 = 25.6 \times 10^{18}$$

corresponding very closely with the present best value from other methods, 27.1 billion-billion. This mode of analysis shows that for dry air, except where selective absorption occurs, the depletion of the beam from the sun or other celestial body, as observed in 1910 and 1911 at Mount Wilson, was caused almost wholly by molecular scattering. From 0.36 μ to 0.50 μ the depletion is practically wholly of this nature. Then come the great selective absorption bands which, except that near D, have been eliminated from this discussion. Even in the infra-red between these water-vapor bands, molecular scattering accounts for the observed depletion of radiation by the atmosphere.

The same analysis applied to atmospheric aqueous vapor shows that the observed absorption is very much too great to be accounted for by the number of water molecules present. The transmission coefficients found by various observers for liquid water, however (0.21 μ to 0.50 μ), are such as would be expected from this amount of water in vapor form. This leads to the inference that its absorption in liquid form in this region results from molecular scattering. The number of molecules, N_o, computed from the transmission coefficients of liquid water is about

$$N_o = 28. \times 10^{18} .$$

The increased absorption connected with atmospheric water-vapor and the departure of the transmission coefficients from strict proportionality to the inverse fourth power of the wave-length in the sense that the coefficients for smaller wave-lengths are too high leads to the inference that the vapor is loaded with something greater in size than molecules. This loading could be due to dust or ions, although there is not definite evidence why these should be proportional to the amount of water-vapor present.

The presence of nuclei, formed by the action of ultra-violet light on the moisture present in the air, seems perhaps the most satisfactory explanation.

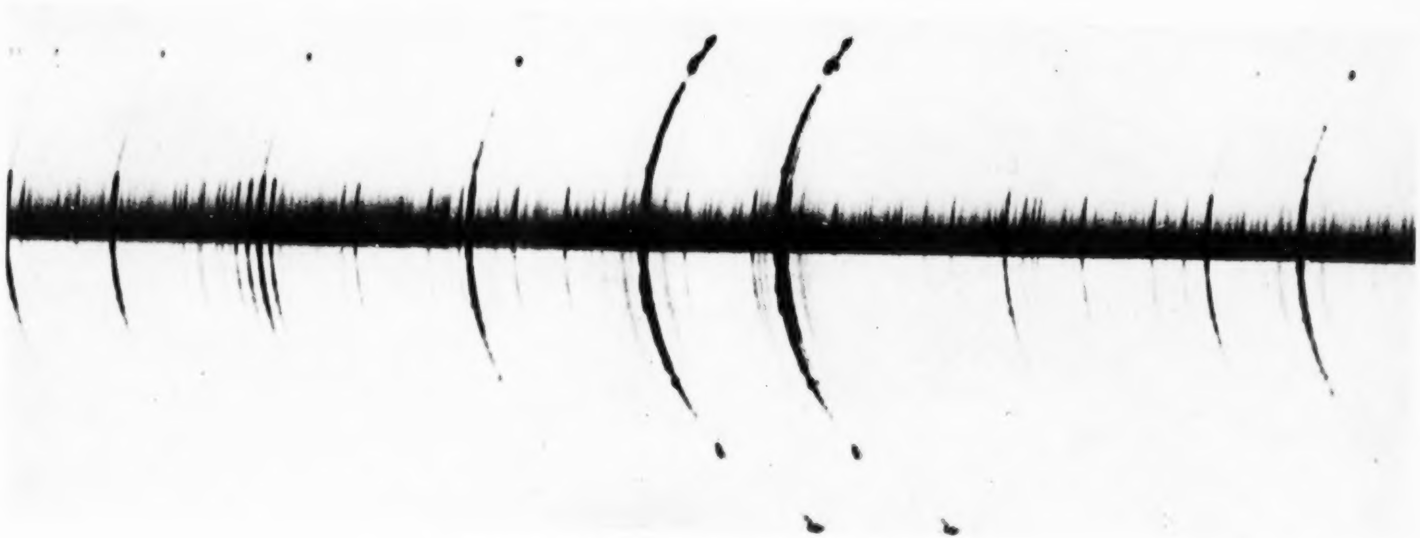
In the above study, as already stated, the amount of water-vapor present in the atmosphere was measured by the depths of three selective absorption lines in the infra-red. The effect of

scattering, which varies slowly and continuously with the wave-length, was eliminated. It was shown in an earlier paper[1] that the mean results of such determinations of the amount of aqueous vapor in the atmosphere agree with the mean results of estimates of it from observations with kites and balloons.

ASTROPHYSICAL OBSERVATORY
SMITHSONIAN INSTITUTION
WASHINGTON, D.C.
June 1913

[1] *Astrophysical Journal*, **37**, 359, 1913.

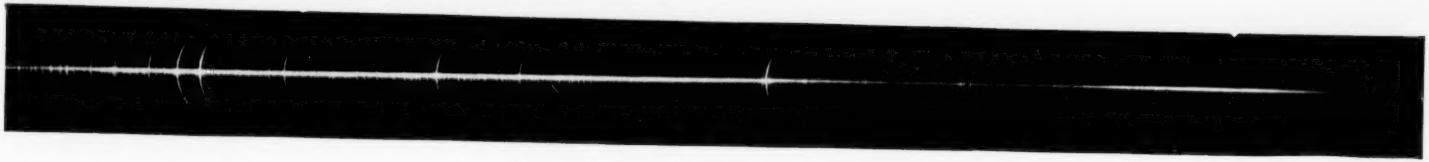
PLATE XIII



Spectrum of Chromosphere—Region of H and K

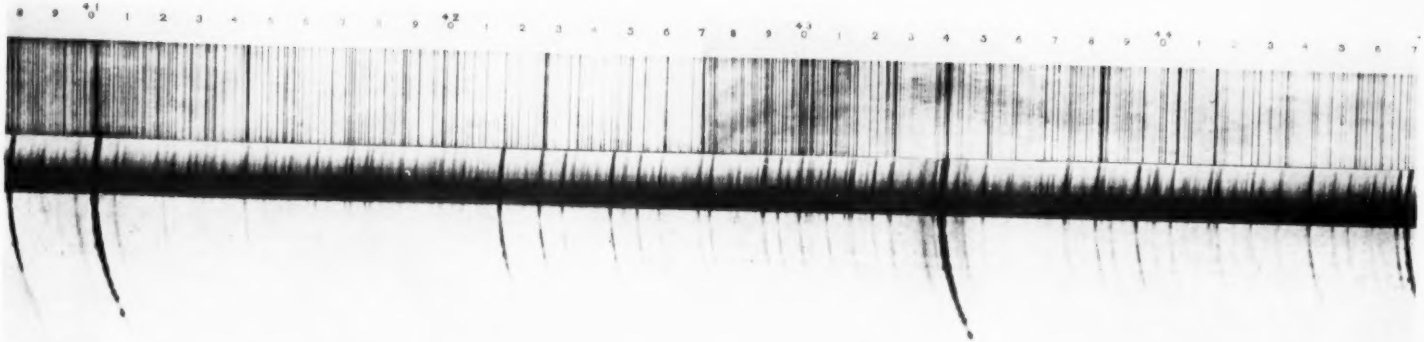
Negative enlarged sixfold

PLATE XIV

a


CHROMOSPHERIC SPECTRUM 1905 ECLIPSE

a. Positive nine-tenths natural size from λ 3700 to λ 5900

b


b. COMPARISON OF FRAUNHOFER AND CHROMOSPHERIC SPECTRA

Above—Rowland's atlas reduced fivefold

Below—Negative of chromospheric spectrum enlarged sixfold